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Mobile experiments using ACTS

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The Advanced Communications Technology Satellite (ACTS), developed and built by Lockheed Martin Astro Space for the NASA Lewis Research Center, was launched in September 1993 on the Shuttle STS 51 mission. ACTS is a digital experimental communications test bed that incorporates gigahertz bandwidth transponders operating at Ka band, hopping spot beams, on-board storage and switching, and dynamic rain fade compensation. This paper describes the ACTS enabling technologies, the design of the communications payload, and some of the terrestrial and aeronautical mobile experiments that have been conducted to date.

1. Introduction

The ACTS satellite was designed to provide Demand Assigned Multiple Access (DAMA) digital communications with a minimum switchable circuit bandwidth of 64 kbps, and a maximum channel bandwidth of 900 MHz. It can, therefore, provide service to thin routes as well as connect fiber backbones in supercomputer networks, across oceans, or to restore full communications in the event of national or man-made disasters.

Although designed for fixed service digital communications, the high gain afforded by the ACTS spot beams and the ability to provide a bent pipe transponder (with the switch matrix held in a fixed state) has also permitted a large number of terrestrial and airborne mobile experiments.

ACTS has proven to be a true orbiting multi-service communications laboratory affording not only a multitude of advances in digital communications, but also the gathering of propagation statistics necessary for the implementation of reliable, Ka band operational systems.

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2. The ACTS system

The ACTS system, shown in Fig. 1, is composed of the ACTS satellite, now in geostationary orbit at 100° West longitude; the Satellite Control Center located at Lockheed Martin Astro Space in East Windsor, New Jersey, which controls the spacecraft and provides 24 hour monitoring of health status; the Telemetry Tracking and Command Station located at the NASA Lewis Research Center in Cleveland, Ohio, which uplinks commands and receives telemetry at Ka band. The NASA Master Control Station (MCS), which controls the Ka band communication network and directs all the experiments, is also located at the NASA Lewis Research Center.

User terminals located throughout the United States complete the ACTS system. These terminals were developed by NASA and are available to users either on loan from NASA or by direct purchase.

The available terminals fall into three broad categories, depending on whether they are used with the Baseband Processor (BBP), the Switch Matrix, or for propagation measurements, features of the satellite that will be described later in the paper.

For the BBP mode of operation, the NASA Ground Station, developed and built by COMSAT, provides control of the TDMA network and directs the traffic to/from eighteen T1 VSAT terminals, developed by Harris, and deployed all over the USA. The NASA Ground Station also serves as a traffic terminal. The U.S. Army has purchased seven T1 terminals, some of which have been ruggedized so they can be transported to simulate battlefield conditions where field deployment and network acquisition are very critical.

For the Microwave Switch mode of operation, a number of terminals have been developed as described below:

a) A Land Mobile Terminal developed by JPL for NASA and used to conduct experiments first in the Southern California area and later in other areas of the country. The data rate supported ranges from 2.4 to 64 kbps.
b) Ultra Small Aperture Terminals developed by NASA Lewis and Southern California Edison for Supervisory Control and Data Acquisition

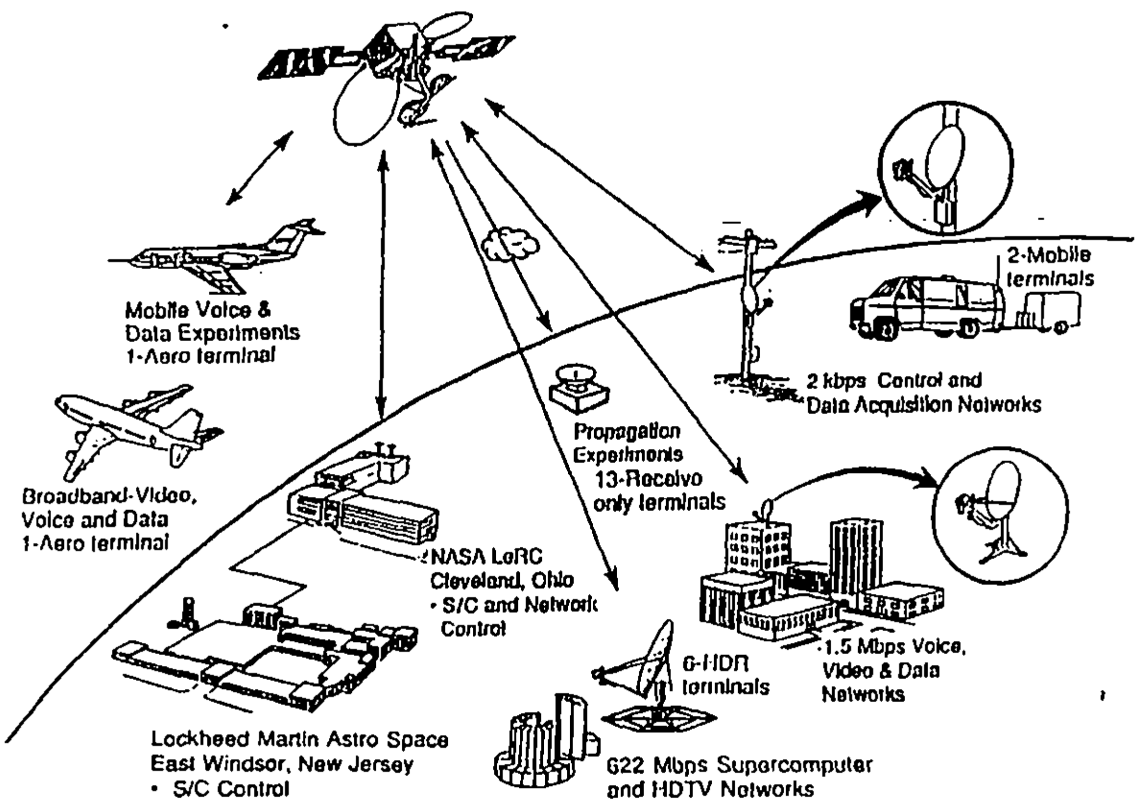

Fig. 1. The ACTS system.

(SCADA) purposes. They have a data rate of about 2 kbps and will be used for monitoring the status of power lines.

c) An Aero-Mobile Terminal developed by NASA Lewis and JPL to provide voice and data to aircraft. It was mounted on a Lewis airplane to conduct the experiment and flown to various U.S. cities.
d) A Broadband Aero-Mobile Terminal is being developed by JPL with Rockwell to provide broadband video, voice and data to aircraft.
e) A Link Evaluation Terminal (LET) developed by NASA Lewis to evaluate the ACTS transponders. It has a data rate of 220 Mbps. In addition to characterizing the transponders, it has been used to perform measurements to locate the center of the Cleveland spot beams.
f) The High Data Rate Terminal (HDR) being developed by NASA in conjunction with ARPA to provide 622 Mbps links between supercomputers for parallel processing experiments. It will also be used for HDTV experiments by PBS.

For propagation measurements, NASA has developed a number of receive-only terminals to be used to characterize the Ka band signal attenuation due to rain. Eight terminals have been built and are deployed in significant rain zone areas to collect statistical data on the frequency and severity of rain fade phenomena.

3. The ACTS technologies

The ACTS satellite communications system contains new technologies that will become the standard of communications satellites of the future. They are:

1) hopping spot beams,
2) onboard switching,
3) Ka band transmission,
4) wide bandwidth channels,
5) rain fade compensation,
6) Ka band propagation beacons.

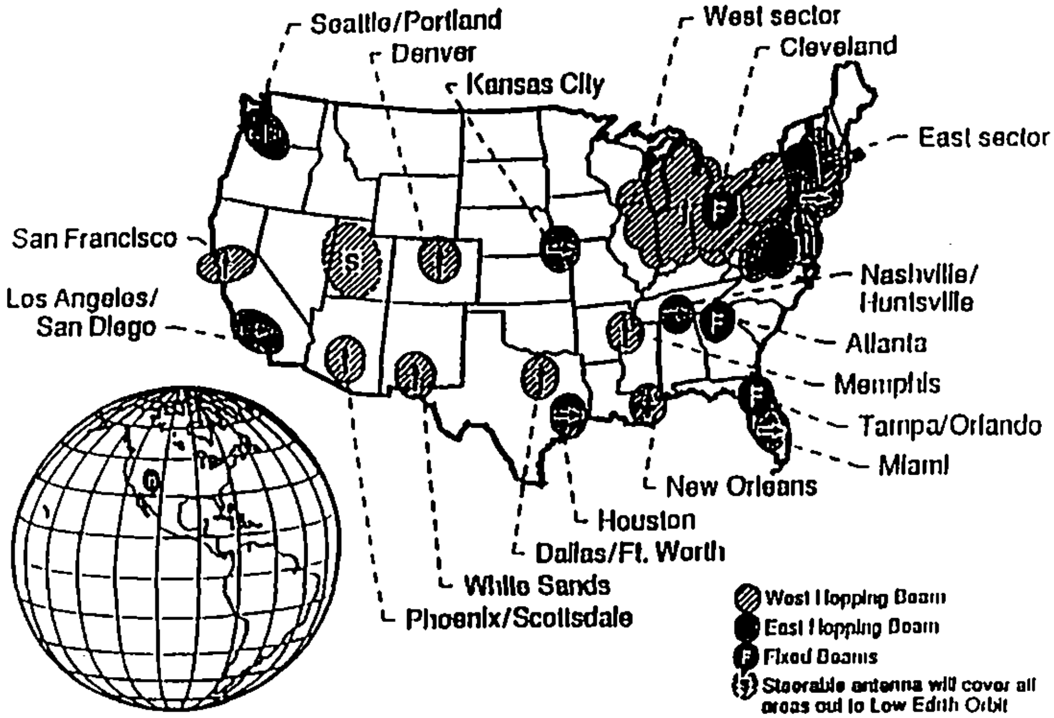

Fig. 2. The ACTS spot beam coverage.

The advantages that these technologies bring to the field of satellite communications are discussed in the following sections of this paper.

3.1. Hopping spot beams

Forerunners to the ACTS satellite have used broad coverage beams that provided relatively low signal levels, requiring large ground receiving antennas and even larger uplink antennas, to the point that the uplink could only be done from very specialized and expensive stations. Spot beams, by contrast, concentrate the energy into small beams with very small footprints, providing in the case of ACTS an improvement of 20 dB in signal level, resulting in small diameter antennas and higher throughput for each earth station. The use of spot beams, however, necessitates a large number of stationary beams or a rather small number of hopping beam families to cover a large geographic area.

The beam locations were chosen on the basis of population density, climate diversity, and availability of data sources commensurate with the high bandwidth channels in the ACTS satellite.

The beams are broken into fixed beams for use with the Switch Matrix, and two families of hopping spot beams for use with the Baseband Processor. However, either type of beam can work with either type of switch to provide on-demand operation in response to traffic needs.

The two families of hopping beams cover two contiguous sectors with uniform gain, a number of isolated spots, and finally a steerable beam to cover Hawaii, Alaska and the entire hemisphere. The fixed and hopping beams all have a 0.3° beamwidth, while the steerable beam has a 1° beamwidth due to the smaller size of the steerable reflector. The ACTS spot beam coverage is shown in Fig. 2.

3.2. Onboard switching

The ACTS satellite has two types of onboard switching; a Switch Matrix to connect the three fixed beams or the two families of hopping beams and a Baseband Processor with storage to control traffic between the two families of hopping beams.

The Switch Matrix provides bent pipe or dynamic switching through transponders having a bandwidth of 900 MHz. When the Switch Matrix is used dynamically, it has a frame of one millisecond with switching states of one microsecond granularity. A frame of 32 milliseconds is also available for low data rate terminals or for applications requiring longer dwell time for each configuration.

In the case of the Baseband Processor, each hopping beam family operates at a maximum throughput of 110 Mbps, with a frame of 1728 slots, for a total TDMA throughput of 220 Mbps. One inherent advantage of baseband processing is that only those beams that are active need to be visited, thus providing demand assigned multiple access (DAMA) channels that make maximum use of available resources on the satellite.

3.3. Ka band transmission

The demand for wireless communications, either terrestrial or by satellite, has created a shortage of spectrum which will become even more acute as less developed areas of the world increase the demand for communications. To alleviate this crowding of the spectrum, ACTS was designed to use Ka band frequencies (30 GHz uplink and 20 GHz downlink), thus developing the technology and the components necessary to build reliable transponders on the satellite and transmitting and receiving stations on the ground.

Ka band has the advantages of increasing the number of satellites that can be placed on the equatorial arc because of the narrow beamwidth that results from the use of the higher frequency, and of reducing the size of the satellite and ground antennas required for any given gain.

One disadvantage of Ka band, however, is its susceptibility to signal loss due to rain, which dictates that suitable measures be taken to compensate for the loss of signal in order to provide reliable, high availability communication channels.

3.4. Wide bandwidth channels

The use of Ka band allows the implementation of very high bandwidth channels. In the case of ACTS, the transponders have a bandwidth of 900 MHz. The availability of such wide channels makes possible the interconnections of supercomputers, the high speed distribution of high density imagery for applications such as remote medical diagnosis, weather and earth resource studies and topographic applications. This large band-width, available on demand, should secure for satellites a pre-eminent place in the implementation of the National Information Infrastructure.

3.5. Rain fade compensation

In order to provide reliable communications, compensation must be provided for the loss of strength, or fading, of the Ka band signal due to rain. Two techniques are used on the ACTS satellite: Increased output of the transmitters and the use of data rate reduction along with convolutional coding.

Increased transmitter power is used in conjunction with the Switch Matrix mode of operation. ACTS has enough RF power to provide a fixed 8 dB link margin on the downlink. The uplink margin is up to 18 dB and can be applied on demand by modulating the power of the ground transmitter.

For the Baseband Processor mode of operation, fading on the downlink is compensated by supplying 3 dB of clear weather margin, supplemented by 4 dB from the use of convolutional coding and 6 dB obtained from frequency and data rate reduction. For the uplink, the clear weather margin is 5 dB, so a total of 15 dB can be provided when coding and data rate reduction are invoked. The fade compensation for both uplink and downlink is applied on demand only to those stations that require it.

The Baseband Processor provides fade compensation by setting aside a number of slots in a 'fade pool'. When a station experiences fading, its burst is moved from the clear part of the frame to the fade pool area where a fourfold increase in the number of slots can be provided without disturbing the other stations burst time plans. The size of the 'fade pool' is a system parameter that is adjusted as needed to provide adequate service and still maintain good frame efficiency.

3.6. Propagation beacons

The ACTS satellite is equipped with stable beacons operating at 20 and 27 GHz and covering primarily the Continental United States.

The beacons are monitored by a number of propagation-only stations to provide the data for developing a comprehensive rain fade model that can be used to optimize the type and amount of fading compensation that would be needed for a given class of service in future operational systems.

4. The ACTS communications payload

A detailed block diagram of the ACTS Communications Payload is shown in Fig. 3. Uplink signals can be received through three fixed spot beams, located at Tampa, Cleveland and Atlanta. These, in conjunction with the Microwave Switch Matrix form the High Burst Rate (HBR) system, which is capable of serving three demand-assigned TDMA channels with bandwidth of 900 MHz each.

Uplink signals can also be received through two families of hopping spot beams steered through East and West Beam Forming Networks which, in conjunction with the Baseband Processor, form the Low Burst Rate (LBR) system, intended to provide demand assigned TDMA thin route circuits of 64 kbps. These can be aggregated to provide wide bandwidth channels up to the maximum capacity of 110 Mbps for each of the two channels of the Baseband Processor.

The Cleveland uplink fixed beam is equipped with a special tri-mode horn that also receives the command carrier. This is processed through an Autotrack Modulator and Receiver to provide an error signal to the spacecraft that maintains the receive antenna locked on Cleveland, thus providing the fine pointing of 0.025° needed for the small diameter (0.30) spot beams.

Each of the uplinked signals can be directed to any of four receivers by means of the Waveguide Input Redundancy Switch (WIRS). The receivers use HEMT inputs and downconvert the input from 30 GHz to the 3 GHz IF used by the Microwave Switch Matrix (MSM) or the BBP. The receivers provide saturated outputs to the MSM, and linear outputs to the BBP Demodulator. The IF outputs of the receivers can be directed to either the MSM or the BBP by means of a Receive Coaxial Switch Assembly. After processing by either the MSM or the BBP, signals are switched through the Transmit Coaxial Switch Assembly to any of four upconverters which upconvert the IF signals to 20 GHz for amplification in the 46 Watt Traveling Wave Tube Amplifiers (TWTA). The outputs of the TWTA can be directed by the Waveguide Output Redundancy Switch to any of the fixed beam or scanning beam ports of the Transmit Antenna.

The key specification parameters of the payload are shown in Table 1, but some additional information on the MSM and the BBP will be provided here.

The MSM is a four-by-four matrix providing cross-point switching from any input to any, or all, outputs. Its bandwidth is 900 MHz, and the switching speed is 100 nanoseconds. It provides a 1 msec or 32 msec TDMA frame with switching at the 1 μsec or 32 μsec boundaries. Switching is controlled by a Ping-Pong memory, so that while the foreground memory controls the present TDMA plan, the background memory can be programmed through the command link to implement the next TDMA plan, which is invoked by swapping the control from the foreground to the background memory. The memory provides telemetry of the active switch states for ground verification before swapping of control.

The Baseband Processor is much more complex than the MSM. It demands an exact protocol, specific signal modulation (SMSK) and frequency, and burst timing within a 60 nanosecond window. It provides demodulation, convolutional decoding, storage, switching, convolutional coding and remodulation of thin route circuits with 64 kbps bandwidth. Convolutional coding and decoding is coupled with data rate reduction to achieve an on-demand margin improvement of 10 dB to selected uplink and downlink stations, when these experience fading due to rain. The BBP is a memory-mapped processor receiving its operating instructions via in-band commands (orderwires) from the Master Control Station located in Cleveland. The BBP has a 1 msec frame and can handle a total thruput of 220 Mbps with its two channels.

Both the MSM and the BBP control the switching of the hopping beams as dictated by the TDMA frame, dwelling only at those locations requiring service for a true demand-assigned operation. The hopping beams thus switch very fast, typically in less than 1 μsec, and can visit a maximum of 40 dwells in a given 1 msec frame.

Although a part of the Command/Ranging and Telemetry Subsystem, two very stable beacons operate in conjunction with the payload to provide fade data. The beacon at the uplink frequency is actually set at 27.505 GHz to avoid interference with the communications signals. The downlink frequency beacon, set at 20.185 GHz, also serves as a carrier for telemetry and ranging. Telemetry data modulates a 64 kHz subcarrier which is always present. An unmodulated 32 kHz carrier is used as a placeholder when not ranging, and is replaced by ranging tones when ranging. The amplitude of the ranging tones is adjusted to produce the same carrier modulation as the 32 kHz subcarrier, to maintain the beacon carrier amplitude constant.

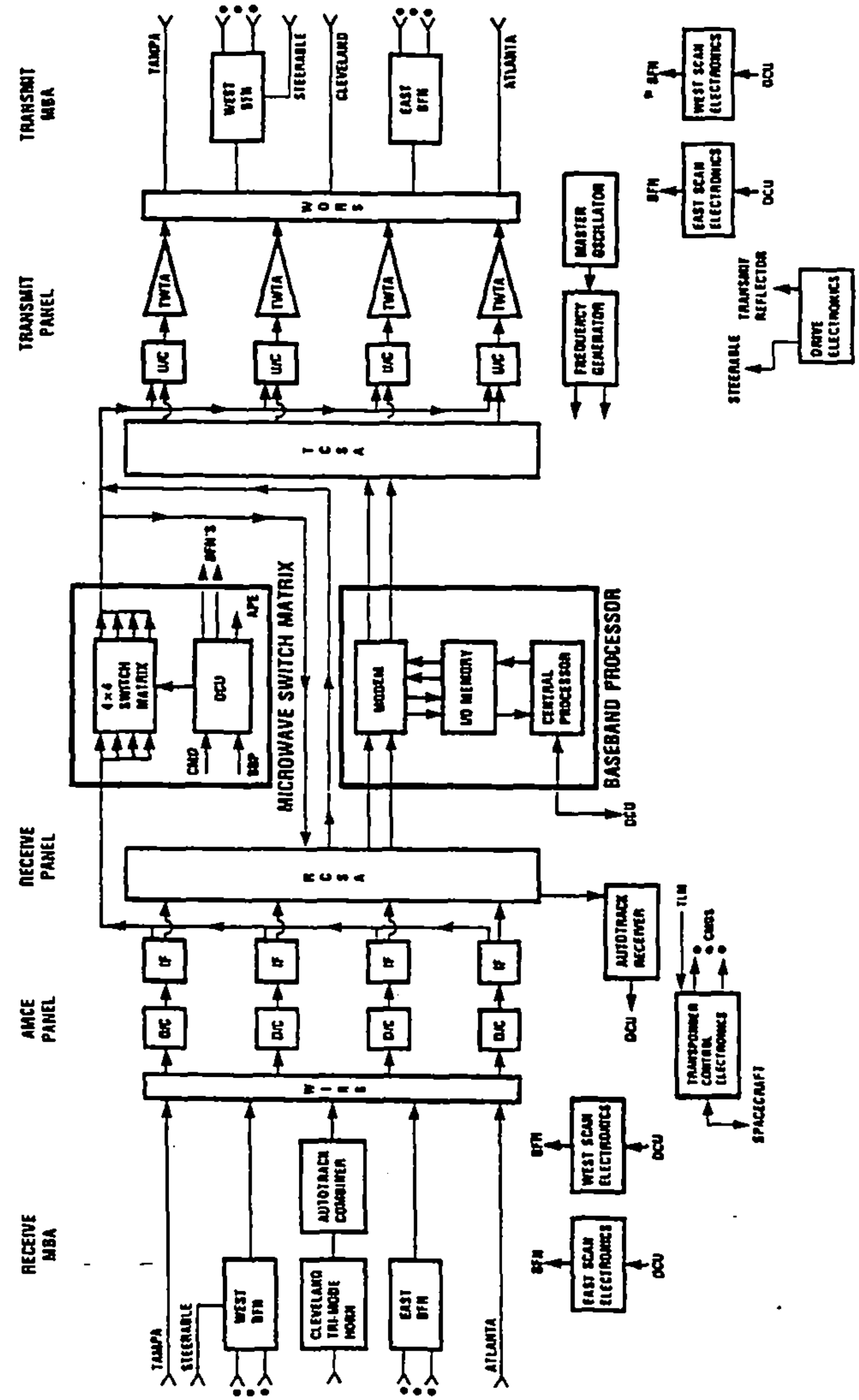

Fig. 3. ACTS communications payload.

Table 1
MBA and communications payload specifications

Frequency	3 Ka Band channels
Bandwidth	900 MHz each channel, 2.7 GHz total
RF Power	46 Watts/channel
Redundancy	1 Standby channel (4 for 3 redundancy)
Coverage	Two contiguous sectors in Northeastern U.S. plus sixteen isolated spot beams covering selected U.S. locations. Also full visible earth coverage via mechanically-steerable spot beam
Receive antenna	2 m dish and 1 m steerable
Transmit antenna	3.3 m dish and 1 m steerable
EIRP	Isolated spot beams: 60 dBW Contiguous sectors: 59 dBW Steerable beam: 53 dBW
Receiver noise figure	3.4 dB (HEMT Front-End)
On-board switching	High speed programmable 3 × 3 switch matrix to provide three input and three output high burst rate (HBR) channels with 900 MHz bandwidth. Baseband processor provides demodulation, storage and remodulation of Low Burst Rate (LBR) Data. Two 110 Mbps TDMA/DMA data streams assignable in increments of 64 kbits
Fade beacons	Stable signals radiated from satellite in the uplink (30 GHz) and downlink (20 GHz) frequency bands to permit link fade measurements
Fade compensation, HBR	Power control on uplink as indicated by monitoring fade beacon at uplink frequency. 18 dB design margin on uplink and 8 dB margin on downlink
Fade compensation, LBR	Combination of convolutional coding, data rate reduction and transmitter margin. 15 dB Design margin on uplink and 13 dB margin on downlink
MBA weight	932 lbs
Payload weight	328 lbs

5. JPL terrestrial experiments

Throughout the eighties, NASA through JPL, has been involved in the development and demonstration of system concepts and high risk technologies to enable the introduction of commercial mobile satellite services (MSS). This initial effort occurred at L band (1.5–1.6 GHz), and currently commercial L band MSS are available through a host of U.S. and international companies. It is expected that the present allocation for L band MSS, which is already congested, will become saturated by the turn of the century. In view of this, and the already existing non-MSS frequency allocations at other bands (C, X, and Ku bands for example), NASA and JPL have focused on K and Ka bands for further expansion of MSS.

K and Ka bands have outstanding potential for higher data-rate communications and more highly diversified MSS for a number of reasons. Unlike L band, K and Ka bands have a significant amount of bandwidth (500 MHz at each band) already allocated for MSS services (WARC '92). Moreover, these higher frequencies can support antenna designs that, while physically smaller than their L band counterparts, can provide higher gain, often 10 dB or more. K and Ka bands therefore, are excellent candidates for the pursuit of higher capacity services for commercial users, e.g., compressed video.

5.1. ACTS Mobile Terminal (AMT)

The AMT is a proof of concept breadboard terminal designed to incorporate the system and subsystem solutions devised to overcome the challenges of K and Ka band land-mobile and personal SATCOM operations. Studies focusing on K and Ka bands have explored system architectures and multiple access schemes that can form the basis for a viable mobile SATCOM system. It has been shown that for CONUS coverage, a geosynchronous satellite is most practical. A general description of such a system is presented in Fig. 4. A fixed station (or hub) communicates through the satellite with a mobile terminal. The experimental scenario for ACTS and the AMT follows this general description as well. In this Frequency Division Multiple Access (FDMA) scheme, an unmodulated pilot signal is transmitted from the fixed station to the mobile terminal user through ACTS. The pilot is used by the mobile terminal to aid in antenna tracking, and as a frequency reference for

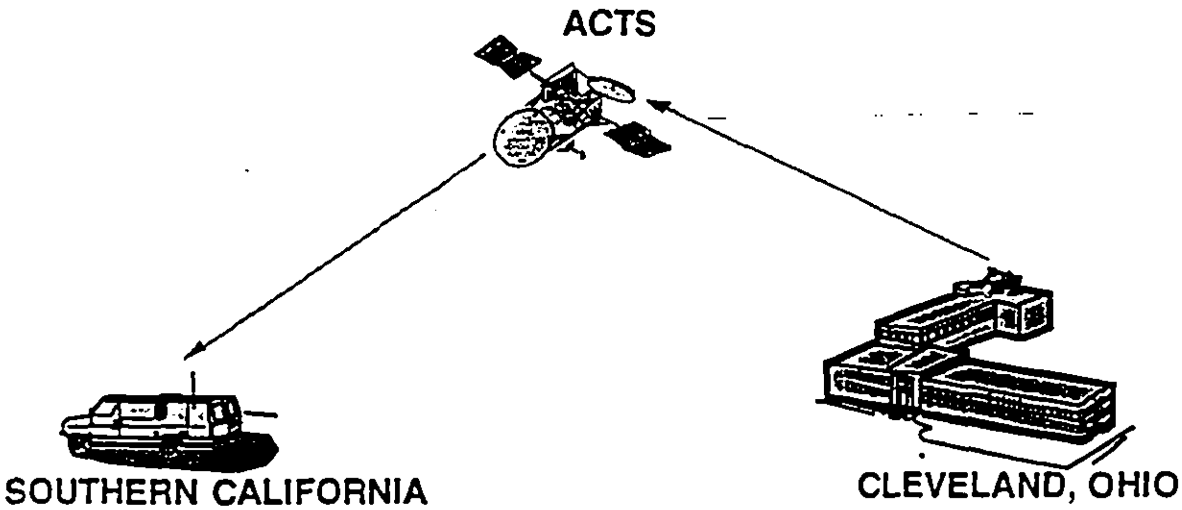

Fig. 4. Basic CONUS satellite system configuration.

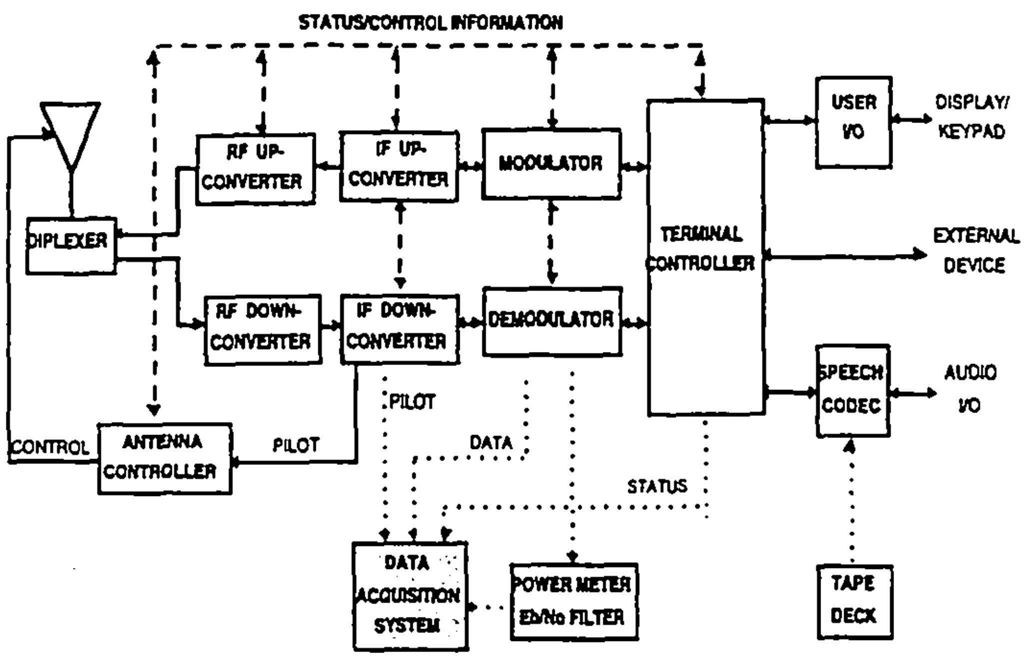

Fig. 5. AMT block diagram.

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Doppler offset correction and pre-compensation. For system efficiency, the pilot signal is only transmitted in the forward direction (fixed station-to-ACTS-to-mobile terminal). Hence for the setup with the AMT, two signals exist in the forward direction, the pilot signal and the data signal. In the return direction (mobile terminal-to-ACTS-to-fixed station), only the data signal is transmitted. Operational data rates for this mobile terminal range from 2.4, 4.8, 9.6, 64 and 128 kbps. A typical set of link budget calculations for both the forward and return communications link are provided in Tables 2 and 3, respectively.

A block diagram of the mobile terminal is provided in Fig. 5. The architecture of the fixed station is identical to that of the mobile terminal with the exception of the antenna. Whereas the mobile terminal utilizes a low-profile, tracking elliptical reflector antenna (less than one foot in size), the fixed station is supplied with a stationary, high-gain, parabolic dish (2.4 meters in diameter). The remainder of this section provides a description of the various subsystem components of the AMT.

Table 2
AMT experiment forward link budget

Uplink: Lewis Research Center Fixed Station to ACTS	
Transmitter parameters	
EIRP, dBW	37.00
Pointing loss, dB	−0.80
Path parameters	
Space loss, dB	−213.48
Frequency, GHz	29.634
Range, km	38000.0
Atmospheric attenuation, dB	−0.36
Receive parameters	
Polarization loss, dB	−0.13
G/T, dB/°K	21.25
Pointing loss, dB	−0.22
Bandwidth, MHz	900.0
Received C/N_0, dB-Hz	71.86
Transponder SNR_{IN}, dB	−17.68
Limiter suppression, dB	−1.00
Transponder SNR_{OUT}, dB	−18.68
Downlink: ACTS to AMT	
Transmitter parameters	
EIRP, dBW	45.04
Pointing loss, dB	−0.32
Path parameters	
Space loss, dB	−209.89
Frequency, GHz	19.914
Range, km	37408.0
Atmospheric attenuation, dB	−0.32
Receive parameters	
Polarization loss, dB	−0.50
Radome loss, dB	−0.20
Antenna gain, dBi	23.00
System temperature, °K	1260.0
G/T, dB/°K	−8.00
Pointing loss, dB	−0.50
Downlink C/N_0, dB-Hz	53.91
Overall C/N_0, dB-Hz	53.82
Required E_b/N_0 (AWGN), dB	6.00
Modem implementation loss, dB	−1.00
Frequency offset degradation, dB	−0.50
Required E_b/N_0, dB	7.50
Phase noise degradation, dB	−1.50
Fade allowance, dB	3.00
Data rate, kbps	4.8
Required C/N_0, dB-Hz	48.81
Link margin, dB	5.01

5.2. Speech codec

The speech codec inputs analog speech signals to a compressed digital representation at data rates of 2.4, 4.8 and 9.6 kbps, with monotonically improving voice quality. The 2.4 kbps compression algorithm is the government standard LPC-10, the 4.8 kbps algorithm is the government-proposed standard CELP, and finally, at 9.6 kbps, an MRELP algorithm has been adopted. The speech codec also contains special design features that make its operation robust in the mobile SATCOM environment with its shadowing-induced outages. Finally, the speech codec allows for connectivity into the Public Switched Telephone Network (PSTN). This allows a mobile terminal user to connect into the PSTN through the satellite and the fixed station.

5.3. Terminal Controller

The Terminal Controller (TC) is the brain of this terminal. It contains the algorithms that translate the communications protocol into the operational procedures and interfaces among the terminal subsystems. For example, it executes the timing and handshake procedures for the interaction among the speech codec, modem, user interface, and any external device (data source or sink) during link setup or relinquishment. The TC also has control over the operation of the IF Converter and RF Converter, and maintains

Table 3
AMT experiment return link budget

Uplink AMT to ACTS	
Transmitter parameters	
EIRP, dBW	22.00
Pointing loss, dB	−0.50
Radome loss, dB	−0.40
Path parameters	
Space loss, dB	−213.34
Frequency, GHz	29.634
Range, km	37408.0
Atmospheric attenuation, dB	−0.44
Receive parameters	
Polarization loss, dB	−0.50
G/T, dB/°K	19.56
Pointing loss, dB	−0.32
Bandwidth, MHz	900.0
Received C/N_0, dB-Hz	54.66
Transponder SNR_{IN}, dB	−34.68
Limiter suppression, dB	−1.05
Transponder SNR_{OUT}, dB	−35.93
Downlink: ACTS to LeRC Fixed Station	
Transmitter parameters	
EIRP, dBW	30.06
Pointing loss, dB	−0.22
Path parameters	
Space loss, dB	−209.03
Frequency, GHz	19.914
Range, km	38000.0
Atmospheric attenuation, dB	−0.50
Receive parameters	
Polarization loss, dB	−0.13
G/T, dB/°K	27.00
Pointing loss, dB	−0.50
Downlink C/N_0, dB-Hz	74.78
Overall C/N_0, dB-Hz	53.58
Required E_b/N_0 (AWGN), dB	6.00
Modem implementation loss, dB	−1.00
Frequency offset degradation, dB	−0.50
Required E_b/N_0, dB	7.50
Phase noise degradation, dB	−1.50
Fade allowance, dB	2.00
Data rate, kbps	4.8
Required C/N_0, dB-Hz	47.81
Link margin, dB	5.77

high-level control over the antenna as well. The TC, in addition, provides the user with the system monitoring capability. Finally, the TC supports the test functions required during experimentation, such as bit stream generation, correlation, and bit error counting and calculation.

5.4. Modem

The baseline AMT modem implements a simple, yet robust differentially coherent BPSK (DPSK) modulation scheme with rate 1/2, constraint length 7 convolutional coding and interleaving. This choice of modulation scheme was mostly dominated by concerns over the performance impact of phase noise onboard the satellite. The performance specification of the modem is a bit error rate of 10^{-3} at an E_b/N_0 of 7.0 dB in an AWGN environment including modem implementation losses. In addition to the 2.4, 4.8 and 9.6 kbps data rates, this modem can also be operated at 64 and 128 kbps. Essential to the modem design is a built-in robustness to deep, short-term shadowing. The modem 'free-wheels', i.e., does not lose synchronization through signal outage caused by roadside trees and will reacquire the data as rapidly as possible after such a drop out. The modem has also been designed to handle possible frequency offsets due to Doppler, and other, frequency uncertainties on the order of 10 kHz changing at a maximum rate of 350 Hz per second. This function is handled through the development and implementation of a rather novel Doppler estimation and correction algorithm.

5.5. IF converter

The IF up/down Converter translates IF signals between 3.373 GHz and a lower 70 MHz IF at the output/input of the modem. A key function of the IF Converter is pilot tracking and Doppler precompensation. The down-converted pilot is tracked in a phase-locked loop (PLL) and used as a frequency reference in the mobile terminal. The tracked pilot is also processed in analog hardware, and mixed with the up-converted data signal from the modem to pre-shift it to offset the Doppler on the return communications link.

5.6. RF converter

Preceding (or following) the antenna, the RF up/down Converter converts an IF signal centered around 3.373 GHz to/from 29.634/19.914 GHz for transmit/receive purposes. The RF Converter also provides the antenna with sufficient power on the transmit signal to complete the communications link.

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5.7. Reflector antenna

The vehicle antenna is the critical K and Ka band technology item developed as part of this terminal design. A 'passive' elliptical reflector-type antenna has been used in conjunction with a separate high-power amplifier (10 Watts output RF power). This antenna was designed to provide a minimum transmit EIRP (on boresight) of 23 dBi, a transmit G/T (also on boresight) of -5 dB/°K, and a bandwidth of 300 MHz. The reflector resides inside an ellipsoidal water-repelling randome of outside diameter approximately 8 inches (at the base) and maximum height of approximately 4 inches.

The antenna pointing system enables the antenna to track the satellite for all practical vehicle maneuvers. This antenna has been mated to a simple, yet robust, mechanical steering system. A scheme wherein the antenna will be smoothly dithered about its boresight by about a degree at a rate of 2 Hz is used. The pilot signal strength, measured through this dithering process, is used to complement the inertial information derived from a simple turn rate sensor. The combination of these two processes maintains the antenna aimed at the satellite even if the satellite is shadowed for up to ten seconds. This mechanical pointing scheme is one of the benefits of migration to the K and Ka bands. The considerably smaller mass, and higher gain achievable relative to L band, make the mechanical dithering scheme feasible and obviate the need for additional RF components to support electronic pointing. The necessary processing resides in the antenna controller.

5.8. Data Acquisition System

The Data Acquisition System (DAS) performs continuous measurement and recording for a wide array of propagation, communication link, and terminal parameters (e.g., pilot and data signal conditions, noise levels, antenna direction, vehicle velocity and heading, etc.). The DAS also provides real-time displays of these parameters to aid the experimentors in the field.

5.9. Terminal performance

Initial terminal performance tests were accomplished as part of the AMT baseline experiments. These tests can be grouped into three general categories:

(1) Baseline and mobile bit error rate tests,
(2) Satellite transponder linearity tests,
(3) Mobile propagation tests.

The details and results of each of these three tests are provided in the following section.

5.10. Bit error rate results

The AMT baseline performance with the mobile terminal in a stationary mode, transmitting data from the fixed station to the mobile terminal was characterized. This was accomplished via bit error rate tests, transmitting a Pseudo-Noise (PN) sequence. These tests were completed for 9.6, 4.8 and 2.4 kbps, transmitting only a data signal (no pilot signal).

Determining the terminal's performance via bit-error rate tests is probably the single best method for determining the overall terminal performance, as well as degradations due to various phenomena that have been introduced to the system. The conditions that were required for these baseline bit error rate curves are as follows:

(1) The van was stationary,
(2) The van's engine was turned off,
(3) The power used in operating the terminal was supplied by the AC generator,
(4) The antenna pointing was accomplished using manual mode,
(5) No pilot signal was transmitted – only a data signal.

The test setup for the baseline system performance tests is provided in Fig. 4. A set of baseline bit error rate tests were performed from the fixed station to the mobile terminal. The full definition of baseline bit error rate tests is provided in the previous section. PN sequence data was transmitted from the fixed station's TC and a final bit error rate was determined at the mobile terminal's counterpart. The E_b/N_0 value was once again determined by the E_b/N_0 box prior to and after the actual transmission of the PN sequence, once again using an unmodulated data signal. These two values were then averaged for the test run. This test was performed for all three of the lower operational data rates of the AMT (2.4/4.8/9.6 kbps). Four different E/N values were recorded for each data rate corresponding to final bit error rate values ranging between 10^{-5} and 10^{-1}.

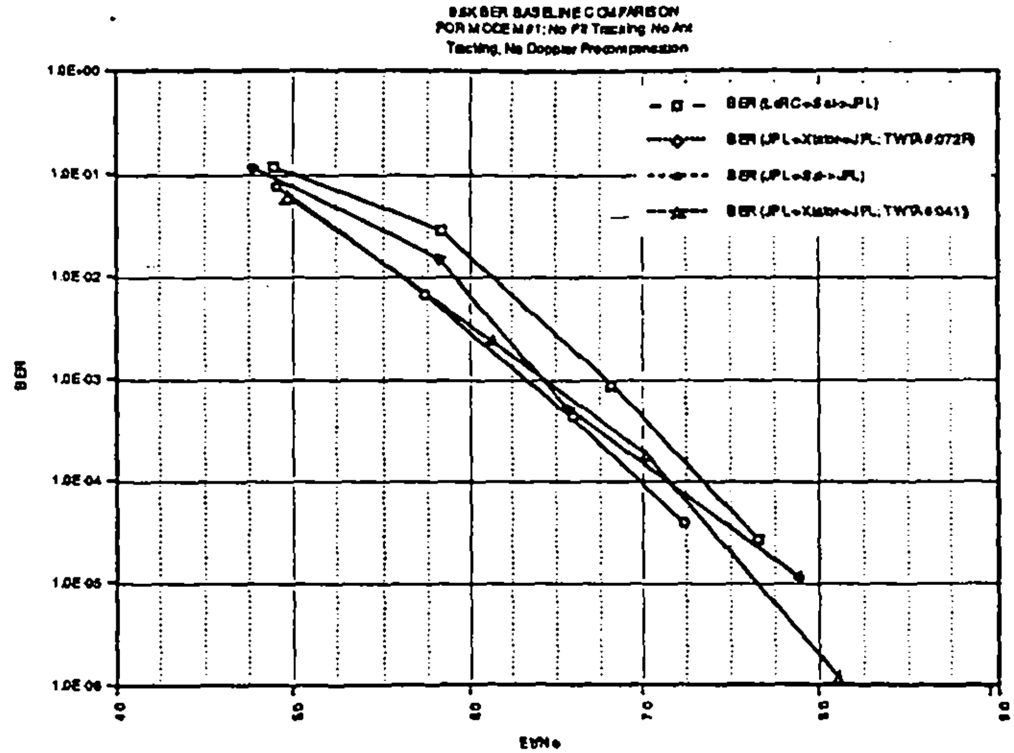

Fig. 6. AMT BER results (9.6 kbps).

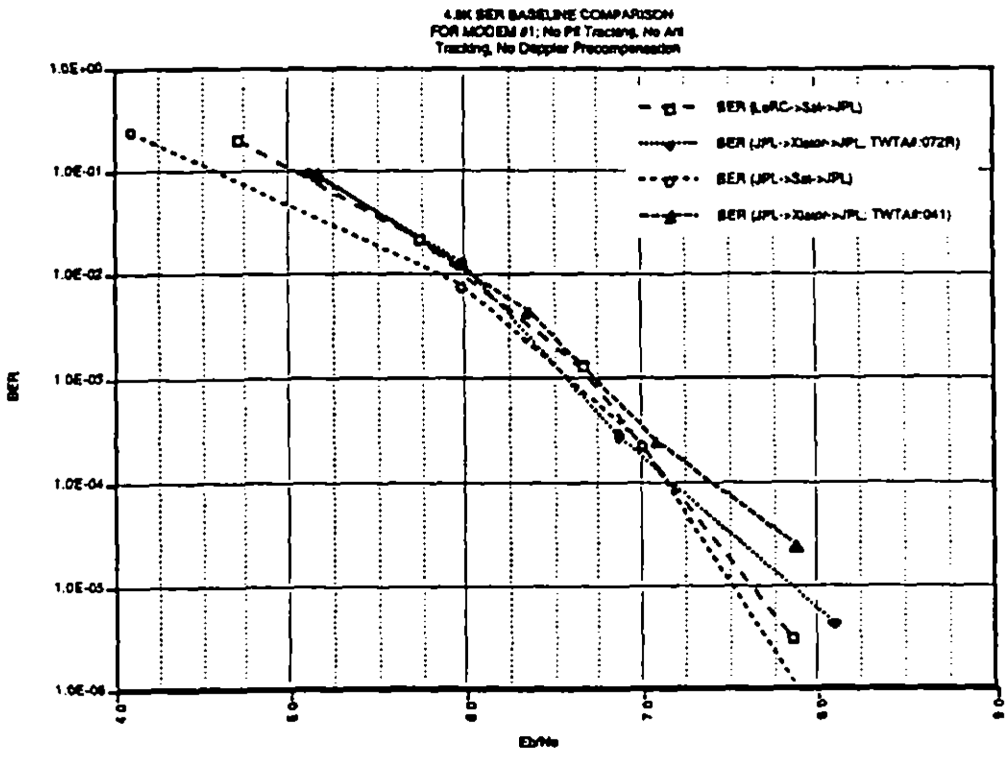

Fig. 7. AMT BER results (4.8 kbps).

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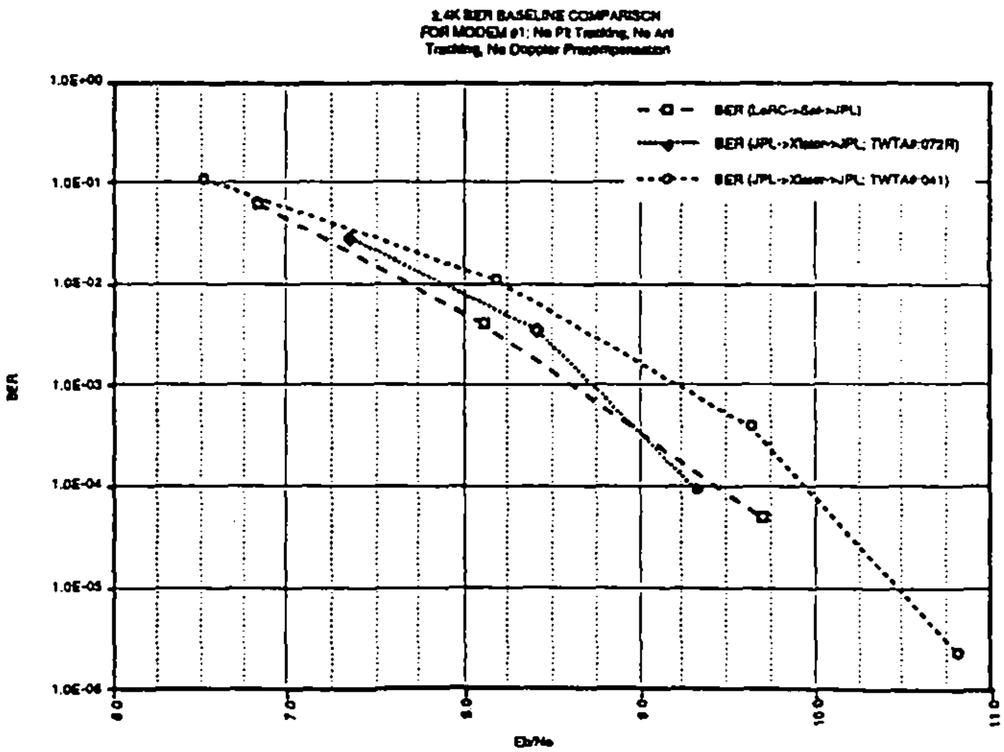

Fig. 8. AMT BER results (2.4 kbps).

The baseline AMT bit error rate performance curves for 2.4, 4.8 and 9.6 kbps are presented in Figs 6 through 8, respectively. For comparison purpose, the Integration and Phase test results, which utilized a satellite simulator, have also been included, listed as Xlator in these figures. Both of these results agree to within experimental error (0.25 dB or less) with each other. For terminal operation at a 9.6 kbps data rate, an E_b/N_0 of 6.8 dB is required to achieve a bit error rate of 10^{-3}. For the 4.8 and 2.4 kbps cases, this performance level is achieved for an E_b/N_0 level of 6.7 and 8.5 dB, respectively.

The terminal's performance during initial mobile SATCOM tests was evaluated. These tests were subjective in nature – involving driving the van around the Pasadena area, and placing many different phone calls back to the fixed station at NASA Lewis Research Center.

In addition, these tests allowed for the evaluation of certain test functions of the mobile terminal that could not be accomplished during the Integration and Test phase of the AMT project. Functions that were initially tested once regular access to the satellite was established, were as follows:

(1) The antenna tracking was first tested in an actual mobile environment,
(2) The DAS antenna pointing error algorithm was tested,
(3) The quality of the voice across the mobile SATCOM channel was subjectively rated.

The test setup for the initial mobile SATCOM tests is once again provided in Fig. 4. This test was performed over the full-duplex link (both fixed station to mobile terminal and mobile terminal to fixed station). This test was accomplished by placing telephone calls between the two terminals over the satellite, and subjectively rating the voice quality as the mobile terminal moved throughout a variety of terrains (mostly highway and surface streets). Both the fixed station and the mobile terminal initiated calls. Notes were taken as to the cause (shadowing due to trees, buildings, overpasses, etc.) of the various signal outages that occurred. No formal bit error rate tests were conducted during these initial tests.

The mobile tests that were conducted on the highway produced a minimal amount of signal outages, while for the surface street tests, received signal outages occurred more often. These initial tests were accomplished at 9.6 and 4.8 kbps operational data being the more robust.

5.11. *Satellite transponder linearity tests*

The ACTS' transponders that were utilized for the forward link (Cleveland uplink and Los Angeles downlink transponders) and the return link (Los Angeles uplink and Cleveland downlink transponders) were initially characterized. In the forward direction, two different types of linearity tests were performed. Non-linearities throughout the system, such as hard limiting and compression over the mobile SATCOM channel, will affect the overall performance of the terminal. Linearity curves, transmit Effective Isotropic Radiated Power (EIRP) versus received Carrier Power to Power Spectral Noise Density (C/N_0), for a single unmodulated data signal across the satellite channel were obtained for both the forward and return links. A second set of linearity curves were also completed using an unmodulated data signal and a pilot signal across the satellite channel to determine the intermodulation product effects. These linearity curves, when correlated with the bit error rate curves, will allow for an estimation of the degradation due to hardlimiting and compression on-board the satellite.

Satellite transponder linearity tests were accomplished for both the forward (fixed station to mobile terminal) and the return (mobile terminal to fixed station) links. Each terminal (mobile terminal and fixed station) has a different transmit power range. The fixed station site has a maximum transmit EIRP of approximately 75 dBW. The mobile terminal site has a maximum transmit EIRP of approximately 30 dBW. The satellite hardware for the forward and return link involves different transponders, so it was necessary to characterize any differences between these two sets of transponders. Each site has a different receive hardware configuration. It was necessary to characterize these differences as well.

While single signal linearity tests were accomplished in both directions for the link, the dual signal linearity test was only accomplished from the fixed station to the mobile terminal, as the equipment will never be configured in this manner.

The linearity test results for the return link transponders using a single unmodulated data signal are provided in Fig. 9. The satellite's transponders were operating in a linear range for the full range of these tests, including the nominal transmit EIRP for this experiment (22 dBW). The low-end values (< 18 dBW transmit EIRP), do not appear to provide linear results. This was because the received noise became the dominant signal below this value, thus skewing the test results.

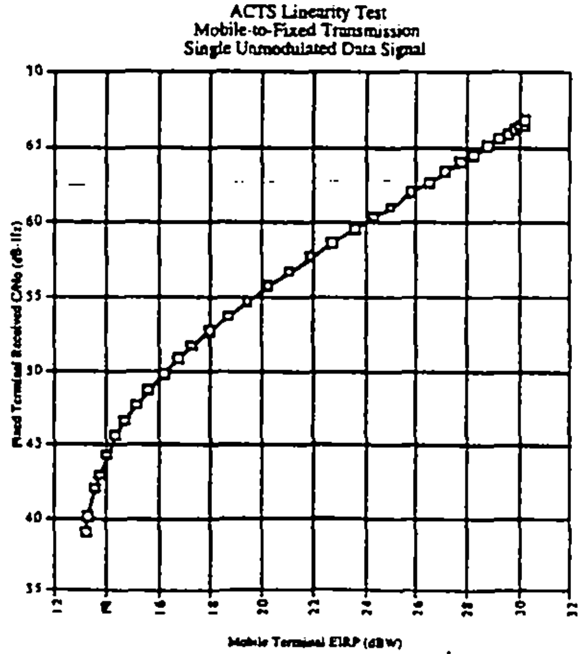

Fig. 9. Return link transponder linearity data (single signal).

The linearity test results for the forward link transponders using a single unmodulated data signal are provided in Fig. 10. The satellite's transponders were operating in a linear range up to a fixed station transmit EIRP value of approximately 50 dBW. Since the nominal transmit EIRP (37 dBW) falls within his range, it will be operating within the linear region of the satellite.

The linearity test results for the forward link transponders using a single unmodulated data signal are provided in Fig. 11. The intermodulation degradation is defined as the percentage of the total received signal power that was present in the unmodulated data signal and the pilot signal. It is further defined as:

$$[Intermodulation\ Degradation]_{db} = 10\log_{10}\frac{P_{data}+P_{pilot}}{P_{data}+P_{pilot}+\sum_{I}P_{i}},$$

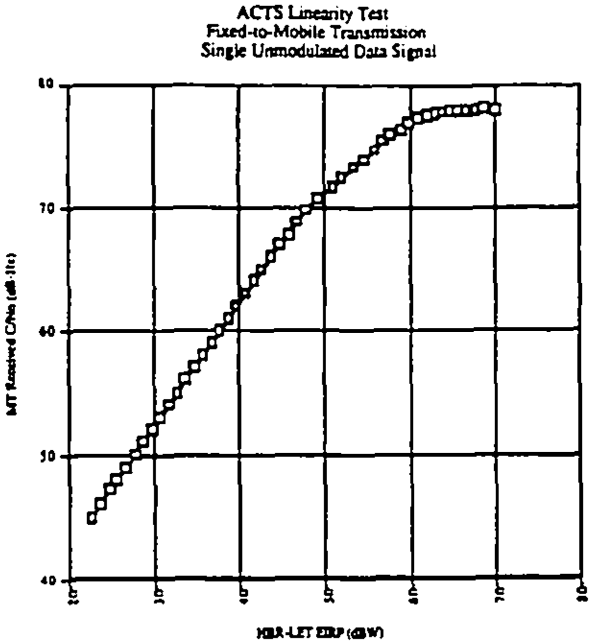

Fig. 10. Forward link transponder linearity data (single signal).

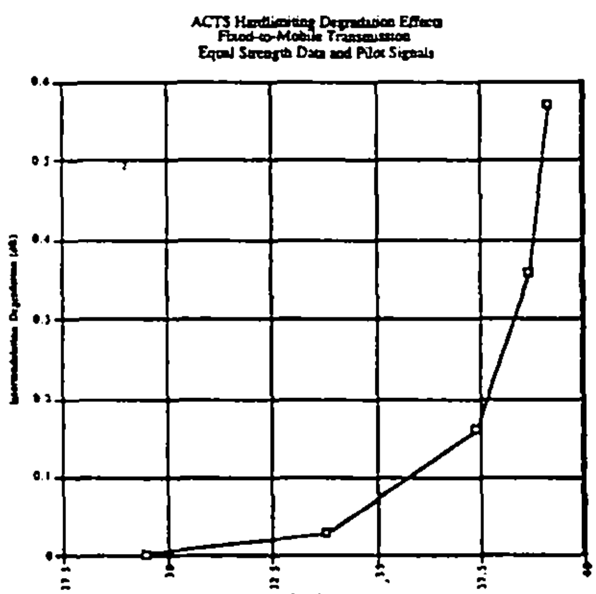

Fig. 11. Forward link transponder linearity data (two signals).

where P_i represents the power in a particular intermodulation product harmonic. For the nominal operational transmit EIRP of 37 dBW, the intermodulation products degradation should be negligible. In fact, for transmit EIRP values of 50 dBW (approximately 30 dB received E_b/N_0 on the accompanying graph) or less, the intermodulation degradation effects are immeasurable. The single signal mobile terminal to fixed station linearity tests showed that the ACTS' transponders utilized for this experiment will be within the linear region for the complete useful range of the mobile terminal's transmit EIRP's. For the same tests that were accomplished from the fixed station to the mobile terminal, the satellite will be operating within its linear region for transmit EIRP's less than 50 dBW. In addition, these initial tests produced other highly positive results. The received C/N_0 was recorded at a level as high as 78 dB-Hz, a value nearly 28 dB higher than that required to operate the terminal at 9.6 kbps. Ultimately, this could lead to a reconfiguration of the AMT for a higher throughput capacity (possible as high as several Mbps), to be used in limited mobile/portable experiments. A negligible amount of intermodulation degradation is present through the satellite for fixed station transmit EIRP's less than 50 dBW.

5.12. Propagation test results

The objectives of the mobile propagation experiments were to measure and analyze the fading characteristics of the K and Ka band channel. The analysis involved examining multipath, shadowing and blockage effects. Field tests were conducted in various environments; results presented here include:

(1) Rural freeway runs free of obstructions except for occasional overpasses,
(2) Shadowed suburban runs with occasional obstructions from buildings, utility poles and trees.

Data from the first category, that is rural freeway runs, was collected on Interstate 210 between California State Highway 2 and California State Highway 118. This is a 15 mile east-west span. A map of this route is provided in Fig. 12. The bold path was the experimental route. A representative time series of the pilot power transmitted by the fixed station, and received at the AMT, is shown in Fig. 13. The statistics of the shadowing/fading are summarized by

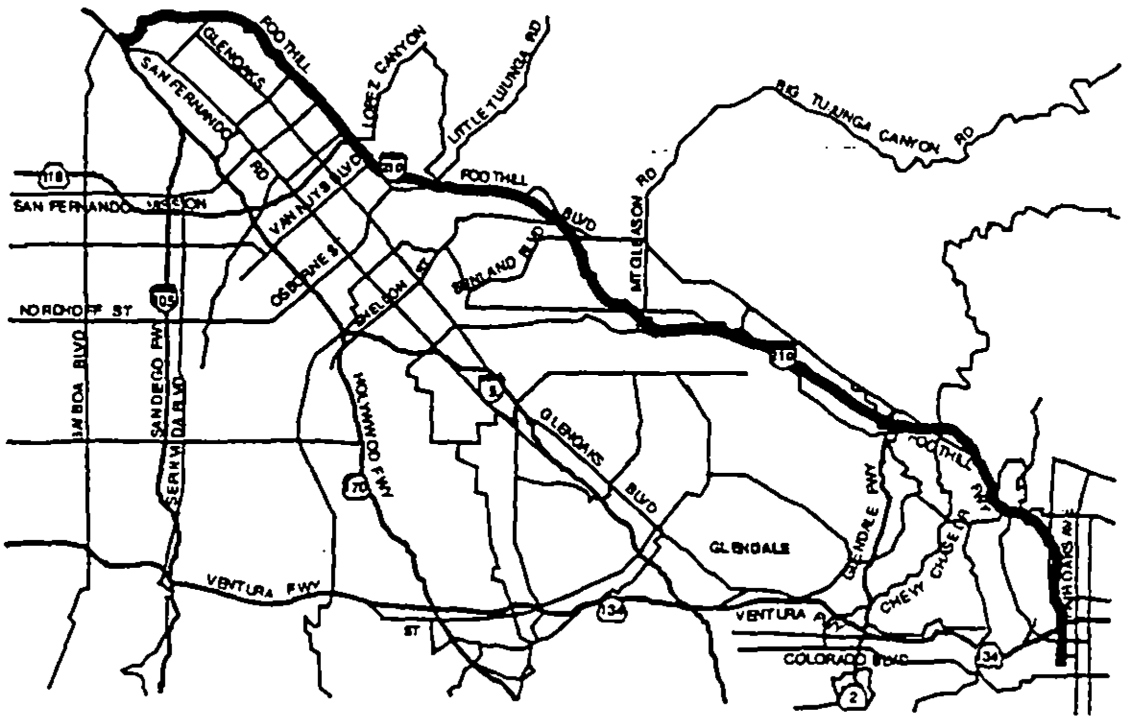

Fig. 12. Map of experimental route (freeway).

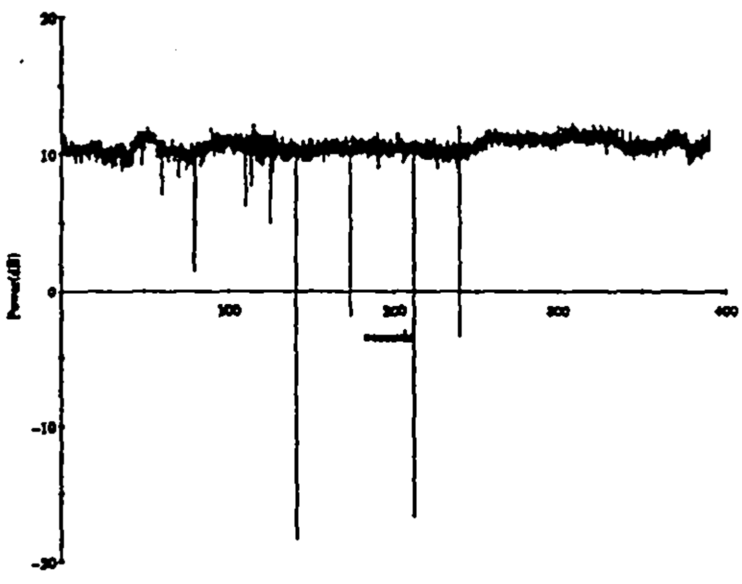

Fig. 13. Typical freeway propagation data (Interstate 210).

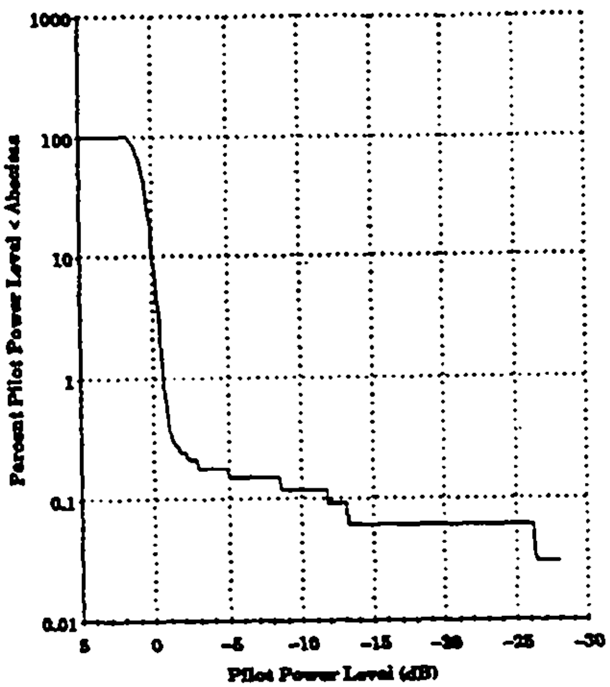

Fig. 14. Cumulative distribution data.

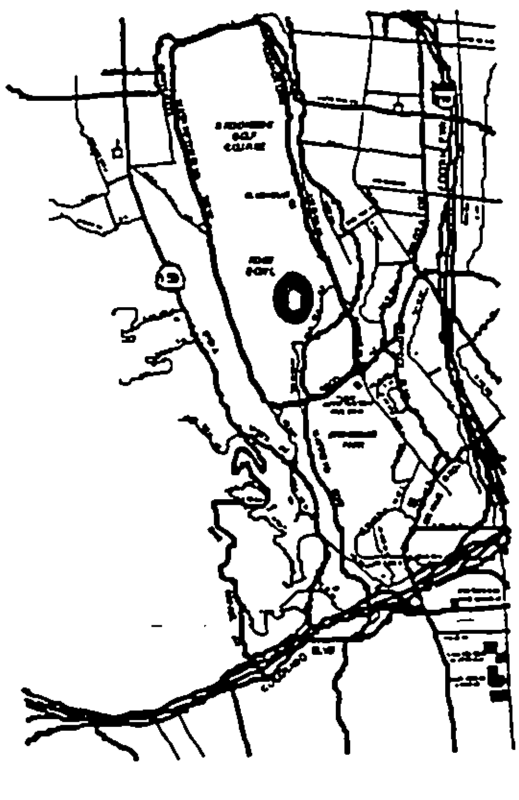

Fig. 15. Map of experimental route (suburban).

a histogram of the cumulative distribution of the pilot power received at the AMT. The histogram of the run shown in Fig. 13, is provided in Fig. 14. It can be seen that the 1% fade level for the 20 GHz channel is 1 dB. This is typical for a clear line-of-sight (LOS) channel.

Data from the second category, that is a shadowed suburban run, was collected on the roads that circle the Rose Bowl in Pasadena, California. A map of this route is provided in Fig. 15. The bold path was the experimental route. The road is surrounded by rolling hills with substantial amounts of foliage. Fig. 16 shows the time series for a test run around the Rose Bowl. The statistics of the shadowing/fading are summarized by the histogram in Fig. 17, where it is seen that the 1% fade level for the 20 GHz channel is 25 dB. This corresponds to a moderately shadowed suburban environment.

The shape of each histogram is typical for mobile satellite channels. The slope from the reference level to 2–3 dB below is steep and consistent with a Ricean characteristic. A transition region, or 'knee' (at 3–5 dB fade levels) precedes a less steep curve for deeper fades. This shallow curve is characteristic of heavy shadowing. These characteristic curves have also been observed on other K band propagation experiments.

5.13. Application specific experiments

Beyond these internal baseline AMT experiments, JPL has been given the task of seeking out and evaluating useful applications for K and Ka band mobile SATCOM and to further demonstrate these capabilities through ACTS and the AMT. To date, twelve different experimenters involving several different government agencies, U.S. industrial interests, and academia have been officially approved to experiment with ACTS and the AMT by NASA Headquarters and the ACTS Project Office at NASA Lewis Research Center. The experiments period began in December 1993, and will continue for at last two years through November 1995. A summary of the mobile experiments is presented in Table 4. Many other experiments are still in the formative stage. Applications-oriented experiments and demonstrations in such areas as emergency medicine, personal communication (PCOMM), disaster recovery, military communications, telemedicine, direct broadcast, and satellite

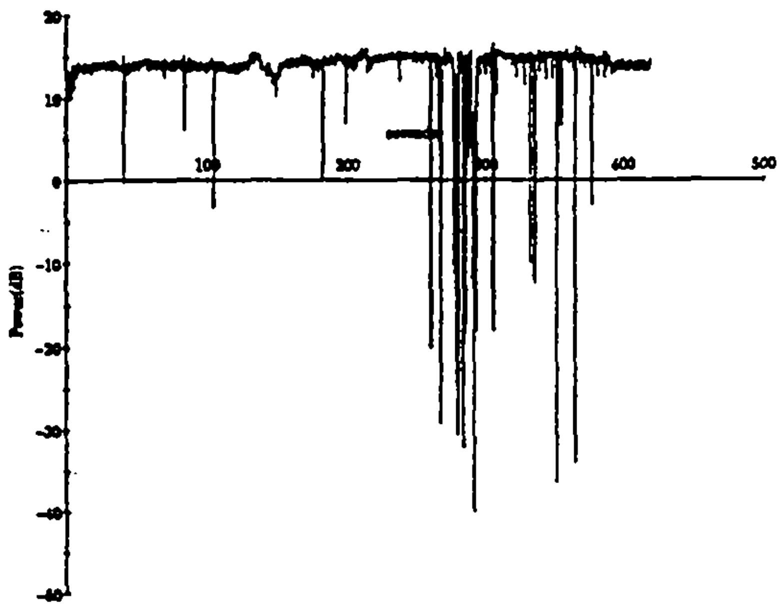

Fig. 16. Typical suburban propagation data (Rose Bowl).

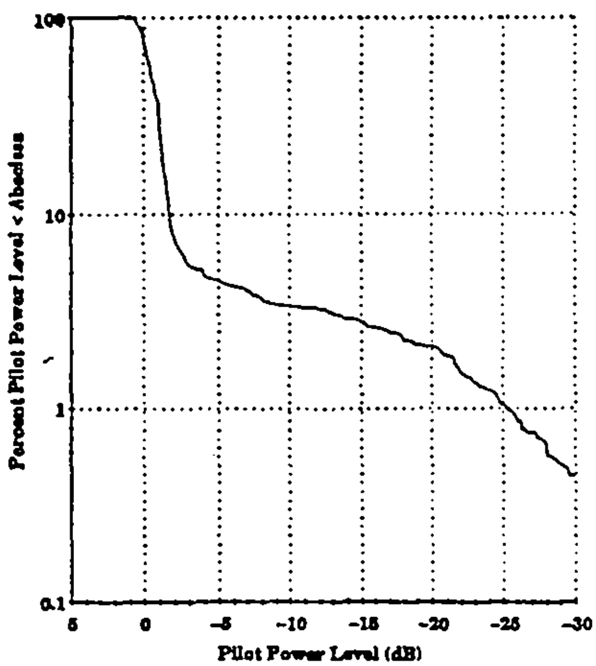

Fig. 17. Cumulative distribution data.

Table 4
AMT experiments

Experiment	Principal investigator
Land mobile, Phase I	JPL
Emergency medical	EMSAT corporation
Secure land mobile, Phase I	NCS
Comm-on-the-move	U.S. Army CECOM
Aero-X	NASA LeRC
Satelllite/terrestrial PCN	Bellcore
Satellite news gathering	NBC
High quality audio broadcast	CBS Radio
Telemedicine	Unversity of Washington Medical Center
Land-mobile, Phase II	JPL
Secure land mobile, Phase II	NCS
Unmanned ground vehicle	ARPA

news gathering (SNG), have been or will be demonstrated.

It is clear that these applications for mobile SATCOM will result in a better overall quality of service within their respective fields. In fact, some of these applications could be offered with current commercial mobile SATCOM systems. The ACTS/AMT experiments that were conducted in emergency medicine and personal communications could be supported today with existing commercial service (e.g., INMARSAT, AMSC) as they are low-bandwidth services. These experiments were conducted strictly to investigate the viability of offering these services via satellite. Other experiments would require an ACTS-like (high capacity) K and Ka band system to fulfill their needs.

5.14. *Experimental results*

The single signal mobile terminal to fixed station linearity tests showed that the ACTS' transponders utilized for this experiment will be within the linear region for the complete useful range of the mobile terminal's transmit EIRP's. For the same tests that were accomplished from the fixed station to the mobile terminal, the satellite will be operating within its linear region for transmit EIRP's less than 50 dBW. In addition, these initial tests produced other highly positive results. The received C/N_0 was recorded at a level as high as 78 dB-Hz, a value nearly 28 dB higher than that required to operate the terminal at 9.6 kbps. (Ultimately, this has led to a reconfiguration of the AMT for a higher throughput capacity to be used in limited mobile/portable experiments.) A negligible amount of intermodulation degradation is present through the satellite for fixed station transmit EIRP's less than 50 dBW.

The baseline system performance test results for the AMT are in agreement with the satellite simulator test results that were accomplished earlier this year. A required E_b/N_0 of 6.8 dB was necessary to operate the system at a BER of 10^{-3} at 9.6 kbps. Similar tests for 4.8 and 2.4 kbps required an E_b/N_0 of 6.7 and 8.5 dB, respectively.

6. JPL aeronautical experiments

Since shortly after the launch of ACTS in September 1993, the NASA/JPL developed AMT has been conducting land-mobile satellite experiments in conjunction with a variety of industry partners. Much has been learned about this communications channel as a result of these experiments. A natural extension of these experiments was to investigate the K/Ka band aeronautical communications channel by installing and testing the AMT in an aircraft. Building on these aeronautical experiments, the ACTS Broadband Aeronautical Terminal was designed to operate at higher data rates (> 384 kbps vs. 4.8 kbps), and without restrictions on the flight path or aircraft dynamics.

6.1. *Use of ACTS*

This experiment requires ACTS to operate in a fixed MSM configuration, in which it behaves as a bent-pipe transponder. The ACTS LA/San Diego spot beam will be used to establish the communication link between the fixed terminal at JPL and ACTS. The ACTS one meter diameter mechanically steerable dish antenna will be used to establish the link between ACTS and the aircraft.

The use of the ACTS steerable dish distinguishes this experiment from the previous ACTS land mobile and aeronautical mobile experiments in that the previous experiments utilized an ACTS spot beam to illuminate the mobile terminal. The benefit of using the steerable antenna is that it removes the restriction that the flight path be within geographically fixed spot beam contours, allowing the aircraft to fly anywhere in the Western hemisphere. The drawback of using the ACTS steerable antenna is that it is smaller and thus has lower gain than the spot beam antennas, approximately 10 dB less on transmit and 7 dB less on receive. This decrease in satellite antenna gain was in part overcome by designing a higher gain antenna on the aircraft.

Use of the ACTS steerable antenna introduces the additional complication of requiring the antenna to continuously track the aircraft. The ACTS steerable antenna has a 3 dB contour of 280 miles, which coupled with a maximum aircraft ground speed of 700 mph, results in a low dynamic tracking requirement. This tracking is accomplished by multiplexing aircraft positioning information (GPS latitude and longitude) with the data stream transmitted from the aircraft to the fixed terminal located at JPL. At the fixed terminal the positioning information is then demultiplexed and transmitted via telephone to the ACTS control station, where the ACTS is then commanded to point the steerable antenna to the aircraft location.

6.2. *Terminal design*

A block diagram of the aeronautical mobile terminal is presented in Fig. 18. The terminal development leverages off the technologies developed under the AMT project at JPL. Therefore the RF converter, IF converter, and DAS subsystems have been adapted from their AMT land/mobile designs to operate in the higher dynamic aeronautical environment. The antenna, power amplifier, modem, and video codec were designed/specified specifically for this aeronautical application. The JPL fixed terminal equipment

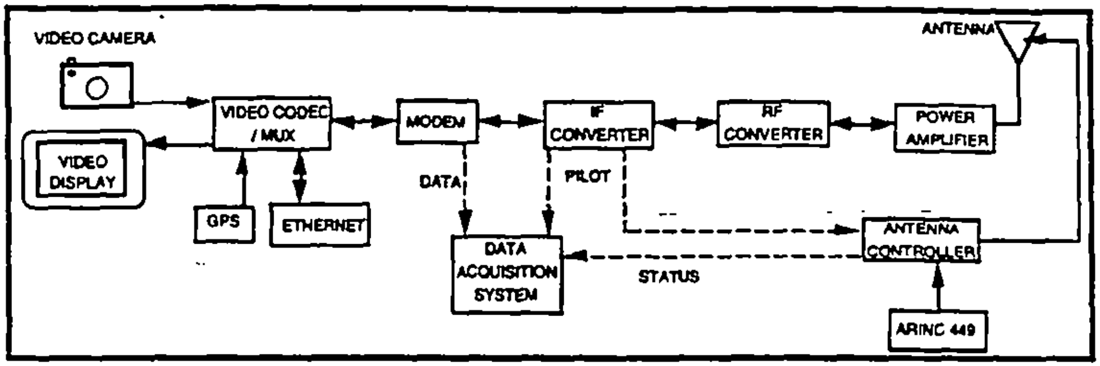

Fig. 18. Block diagram of the broadband aeronautical terminal.

is essentially equivalent to that in the aircraft with the exception of the 2.4 meter ground antenna.

The link budgets for the forward link (JPL fixed terminal-ACTS-aircraft), and the return link (aircraft-ACTS-JPL fixed terminal) are given in Tables 5 and 6. Not shown in the link budgets for simplicity, is the forward link pilot signal. The pilot is transmitted from the fixed terminal to the aircraft as an aid in antenna tracking, Doppler compensation, and link characterization. More detailed descriptions of the subsystems follow.

6.3. Video codecs

The video codec compresses/decompresses full motion video in real time, as well as multiplexes the aircraft position information into the data stream which is then passed to the modem. In evaluating the codec video quality, the performance at data rates from 128 kbps to 384 kbps was deemed to be most important for the planned mobile SATCOM experimental applications.

The ideal video codec for aeronautical mobile applications has characteristics that are not necessarily important when the codecs are utilized in their traditional role of fixed site video teleconferencing. The aeronautical mobile satellite communications channel may have periods of signal outage due to aircraft structure shadowing or the antenna tracking keyhole effect (e.g., keyhole is symptomatic of 2-axis tracking mechanisms, when the tracking direction closely approaches one of the mechanisms rotational axes). Signal outages necessarily require the video codec to regain synchronization rapidly when the signal returns. The best outage recovery performance that could be had with existing video codecs was on the order of three seconds after the codec started receiving valid data. The mobile satellite communications channel typically has a higher bit error rate than do the communication channels which the video codecs typically encounter. As a result, it is critical that the codec degrade gracefully in the presence of high bit error rates, and recover rapidly from these errors.

6.4. Modem

The modem was designed to counteract the peculiarities of the K/Ka band aeronautical communications channel, including varying frequency offsets, phase noise, and signal outages. BPSK modulation is combined with coherent demodulation, and error correction coding is provided by a concatenated code, a convolutional inner code (rate 1/2, constraint length 7) and a Reed-Solomon outer code (rate 239/256). A bit error rate of 10^{-6} is achieved at an E_b/N_0 of 3.0 dB.

Operation at higher bit rates, compared to the AMT, allows the use of coherent differential detection because the high close-in to the carrier phase noise can be tracked out by the wider bandwidth of the tracking loop. The receiver loop parameters also had to be optimized to allow tracking Doppler frequency offsets of up to 30 kHz, varying at 900 Hz/sec. Additionally the synchronization algorithms (carrier, bit and decoder) had to be optimized to allow recovery synchronization within one second of signal presence.

6.5. RF electronics

The IF up/down converter translates between 3.373 and a lower 70 MHz IF at the output/input of the

Table 5
Forward link budget

Forward (JPL to ACTS to aircraft) link budget Uplink: JPL to ACTS	
Transmitter parameters	
Transmit power, dBW	16.7
Waveguide loss, dB	−8.5
Antenna gain, dB_i	54.7
Available EIRP, dBW	62.9
Percentage of EIRP in data signal, %	91.0
EIRP, dBW	62.5
Pointing loss, dB	−0.8
Path parameters	
Space loss, dB	−213.5
Frequency, GHz	29.6
Actual range, km	38000.0
Atmospheric attenuation, dB	−0.4
Receiver parameters	
Polarization loss, dB	−0.1
G/T (EOC), dB/K	17.9
Pointing loss, dB	−0.1
Bandwidth, MHz	900.0
Received C/N_0, dB-Hz	94.1
Transponder SNR_{IN}, dB	4.5
Eff. lim. suppression, dB	−0.2
Hard lim. eff. SNR_{OUT}, dB	4.3
Downlink: ACTS to aircraft	
Transmitter parameters	
Steerable beam minimum peak EIRP	55.7
EIRP, dBW	54.0
Pointing loss (edge of beam), dB	−0.5
Path parameters	
Maximum space loss (10° Elevation), dB	−211.1
Frequency, GHz	19.9
Maximum range (at 10° Elevation Angle), km	42800.0
Atmospheric attenuation, dB	−0.5
Receiver parameters	
Polarization loss: circular W/2dB axial rat., dB	−4.1
G/T (W/Radome), dB/K	0.0
Pointing loss, dB	−0.5
Downlink C/N_0, dB-Hz	65.9
Overall C/N_0, dB-Hz	65.9
Required E_b/N_0 (AWGN – simulation), dB	3.0
Modem implement. loss, dB	1.0
Loss due to frequency offsets/DOP, dB	1.0
Required E_b/N_0	5.0
Loss due to ACTS phase noise, dB	1.0
Data rate, kbps	384.0
Required effective C/N_0, dB-Hz	61.8
Performance margin, dB	4.0

Table 6
Return link budget

Return (JPL to ACTS to aircraft) link budget Uplink: aircraft to ACTS	
Transmitter parameters	
Transmit power, dBW	20.0
BPF & WG losses, dB	−3.8
Antenna gain (W/Radome), dB, C	29.0
EIRP, dBW (nominal)	45.2
Pointing loss, dB	−0.5
Pol. loss: Circ. W/2dB axial rat., dB	−4.1
Path parameters	
Maximum space loss (at 10° elevation angle), dB	−214.6
Frequency, GHz	29.6
Range, km	42800.0
Atmospheric attenuation, dB	−0.4
Receiver parameters	
G/T: Steerable beam peak dB/K	14.5
Pointing loss (edge of beam), dB	−0.5
Bandwidth, MHz	900.0
Received C/N_0, dB-Hz	68.3
Transponder SNR_{IN}, dB	−21.3
Limiter suppression	0.0
Transponder SNR_{OUT}, dB	−21.3
Downlink: ACTS to JPL	
Transmitter parameters	
EIRP (EOC), dBW	41.1
Pointing loss, dB	−0.2
Path parameters	
Space loss, dB	−210.0
Frequency, GHz	19.9
Range, km	38000.0
Atmospheric attenuation, dB	−0.5
Receiver parameters	
Polarization loss, dB	−0.1
G/T, dB/K	25.7
Pointing loss, dB	−0.5
Downlink C/N_0, dB-Hz	84.1
Overall C/N_0, dB-Hz	68.2
Required E_b/N_0 (AWGN – simulation), dB	3.0
Modem implement. loss, dB	1.0
Loss due to frequency offsets/DOP, dB	1.0
Required E_b/N_0, dB	5.0
Loss due to ACTS phase noise, dB	1.0
Data rate, kbps	384.0
Required effective C/N_0, dB-Hz	61.8
Hardware performance margin, dB	6.3

modem. A key function of the IF converter is pilot tracking and Doppler pre-compensation. The down/converted pilot is tracked in a phase-locked loop and used as a frequency reference in the mobile terminal. The loop is capable of tracking out 39 kHz of Doppler varying at 900 Hz/sec. The tracked pilot is also processed in analog hardware and mixed with the up-converted data signal from the modem to pre-shift it to offset the Doppler on the return link. The IF converter provides the DAS and antenna subsystem with a report of pilot signal strength for link characterization and antenna pointing operation respectively.

Preceding (or following) the antenna, the RF (down) converter will convert an IF around 3.373 GHz to (from) 30 (20) GHz for transmit (receive) purposes. The RF converter interfaces directly to the antenna on the receive side of the link. On the transmit side, the RF converter 30 GHz signal goes to TWTA. The TWTA supplies 100 Watts of 30 GHz transmit power to the antenna.

6.6. *Antenna*

The high gain aeronautical antenna employs an azimuth and elevation pointing system to allow it to track the satellite while the aircraft is maneuvering. The aeronautical antenna and radome were developed by EMS Technologies, Inc. The EMS antenna design utilizes a slotted waveguide array, is mechanically steered in both azimuth and elevation, and is designed to enable mounting on a variety of aircraft. The radome is shaped with a peak height of 6.7", and a 27.6" diameter; roughly the size of the SkyRadio radome currently flying on United Airlines and Delta Airlines aircraft. Antenna installation requires a 3.5" diameter protrusion into the fuselage to allow the necessary signals to pass to and from the antenna.

The antenna is capable of tracking a full 360° in azimuth and −5° to zenith in elevation. The antenna RF requirements include that it maintain, in flight, a minimum transmit gain of 29 dBi and a minimum receive sensitivity of 0 dBi/°K. Circular polarization is utilized and there exists the capability to transmit up to 120 Watts through the antenna. The actual dimensions of the combined transmit and receive array apertures are less than 16" wide, and less than 4.5" in height.

The transmit array 3 dB beamwidths are 5° and 2.5° in elevation and cross-elevation respectively. The receive array 3 dB beamwidths are 7° and 4° in elevation and cross-elevation respectively. The antenna tracking mechanism is required to maintain pointing within 0.5 dB of beampeak throughout all phases of flight. This is accomplished through a tracking algorithm that utilizes three sources of information: An inertial 3-axis rate sensor, the aircraft Inertial Navigation System (INS), and pilot signal strength feedback from a circular dithering of the beam. The rate sensor provides the primary information for accurately pointing the antenna, with the INS and the dithering mechanisms being used to adjust for long term drift of the rate sensor. The antenna control computer outputs all relevant parameters (e.g., antenna direction, aircraft velocity, pitch, roll, yaw, etc.), to the DAS for recording and post-flight analysis.

6.7. *Experiments*

The initial three experiments to be conducted with the aeronautical terminal are shown in the accompanying Figs 19, 20 and 21. The NASA Ames Research Center is flying the terminal in the Kuiper Airborne Observatory (KAO) to transmit imagery from the aircraft for an educational broadcast and to conduct remote tele-science. Rockwell/Collins is working with JPL to develop the terminal and integrate it into a Rockwell Saberliner aircraft to demonstrate the transmission of compressed video, both to and from the aircraft. A separate group at the NASA Ames Research Center is planning an experiment to demonstrate the real-time transmission of sensor data from aircraft that perform disaster assessment flights (e.g., wildfire assessment). Additional experiments being discussed involve transmittal of real-time graphical map information to the cockpit, aeronautical remote sensing applications for fixed wing and rotary wing aircraft, and military aircraft applications.

6.8. *KAO/ACTS experiment*

JPL, working cooperatively with NASA Ames, is conducting a series of experiments on the KAO that will utilize ACTS. These experiments are taking place from June through September 1995. The JPL-developed ACTS Broadband Aeronautical Terminal has been installed in the KAO C-141 aircraft to al-

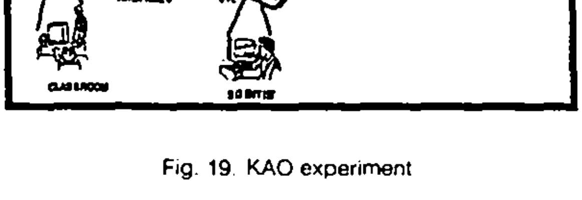

Fig. 19. KAO experiment

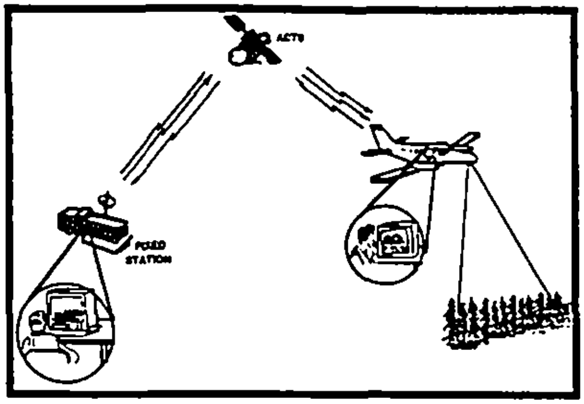

Fig. 20. Rockwell/Collins experiment.

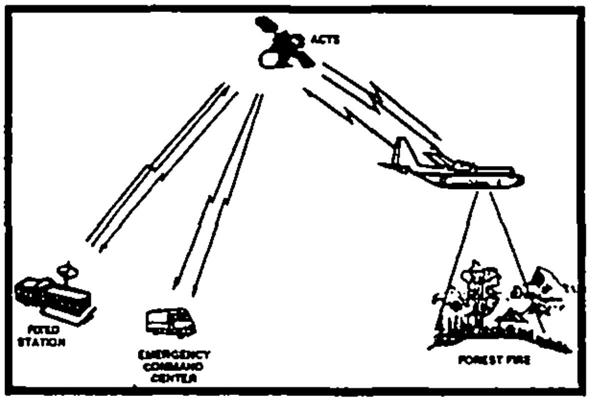

Fig. 21. Wildfire research and disaster assessment experiment.

low the establishment of a full-duplex satellite communications link between the aircraft and the ground. There are currently four planned components of this experiment. These are:

(1) Television broadcast/interactive classroom – a PBS produced live television broadcast entitled 'Live from the Stratosphere'. As part of the broadcast, students watching the live video transmitted from the aircraft will be able to ask questions via voice link to the aircraft.
(2) Video downlink to the San Francisco Exploratorium and Adler Planetarium in Chicago.
(3) Telescience demonstration of remote control of scientific instruments on-board the KAO via an extension of Internet connectivity to on-board the aircraft.
(4) System Health Monitoring demonstration of a system that remotely monitors scientific instruments on-board the KAO via Internet.

6.9. *Rockwell/Collins experiment*

Rockwell International/Collins Corporation Commercial Aeronautical Services and JPL are currently working together on an experiment design that will investigate the feasibility and limitations of airborne Ka band satellite communications. This experiment involves the installation of the Broadband Aeronautical Terminal into Rockwell's Saberliner 50 aircraft for a series of demonstration flights. The specific objectives of this experiment are to:

(1) Determine the feasibility of high data rate communications, in particular compressed full motion video, to and from an airborne platform under varying weather conditions.
(2) Determine the feasibility of slaving the steerable satellite antenna to an on-board aircraft Global Positioning System (GPS) receiver in order to automatically follow the flight path of the aircraft, allowing the highest possible data rate channel for critical applications.

This experiment has applications to both commercial aviation and government airborne services. Commercial airlines wish to offer live video and high bandwidth multimedia services to passengers, but currently do not have the necessary bandwidth capacity to/from the aircraft. Various government entities have mission requirements to transmit and receive real-time video between airborne mobile terminals and fixed earth terminals. This experiment is slated to take place during the latter part of 1995.

6.10. *Wildfire research and disaster assessment experiment*

In 1996, NASA Ames and JPL will be installing the Broadband Aeronautical Terminal in either a C-130 or Learjet to perform fire research and assessment during a prescribed burn and an actual wildfire in Southern California.

Airborne sensors that generate imagery of the fire will be uplinked from the burn site and relayed through ACTS to researchers and disaster assessment managers at various agencies. This 'telepresence' can enable experts at the U.S. Forest Service, Federal Emergency Management Agency, Office of Emergency Services, and the California Department of Forestry to direct and/or monitor various phases of the activities at the remote fire site.

The experience gained from merging remote sensing and mobile satellite communications used in the management and assessment of the prescribed burn experiment can lead to their application in real-life wildfire situations. Also, the experience gained from this proposed experiment will, hopefully, contribute to more effective long-term policy of wildfire management, and to improved coordination procedures in more general emergency situations such as hurricanes, floods, volcano eruptions and oil spills.

6.11. *Experimental results*

To date, the Broadband Aeronautical Terminal has been installed on the KAO C-141 aircraft. During the flight tests completed to date, the terminal performed quite well. The system has been able to acquire the satellite signal prior to take-off and remain locked during take-off, cruise and landing, maintaining a full-duplex compressed video link the entire time. Preliminary measurements of signal-to-noise ratio for the signal received in the aircraft and at the fixed terminal indicate that the terminal performance is better than predicted by the link budgets, and full-duplex T1 data rate (1.544 Mbps) can be supported.

7. NASA Lewis Research Center aeronautical experiment

During the summer of 1994, the performance of an experimental mobile satellite communication system was demonstrated to the industry and government representatives by the NASA Lewis Research Center (LeRC) and JPL. The system was based on ACTS and consisted of a K/Ka band active MMIC phased array antenna system, AMT and LET. A LeRC research aircraft, Learjet Model 25, was outfitted with the active MMIC phased array antenna system and AMT, and served as the experimental 20/30 GHz aeronautical terminal. The LET at LeRC in Cleveland, Ohio, was interfaced with portions of fixed-AMT equipment and together provided the gateway station functions including ACTS satellite interface and PSTN interface. The ACTS was operated in its MSM mode with a spot beam for the Learjet and another spot beam dedicated to the LET. The Learjet was flown over several major cities across the U.S. and demonstrated the feasibility of full-duplex compressed voice link for an aeronautical terminal through the 20/30 GHz ACTS satellite channel. This paper presents a technical description of the system including the MMIC phased array antenna system, AMT, Learjet, LET and ACTS satellite. The array antenna system consists of a 30 GHz transmit array (LeRC/Texas Instruments) and two 20 GHz receive arrays (U.S.A.F. Rome Lab/Boeing and Lockheed Martin), each one very small with sufficient performance for a satellite voice link. The AMT consists of 2.4/4.8/9.6 kbps voice coder/decoder, modem, PSTN interface and RF/IF converters. Link analyses are presented and compared to the actual performance data collected during the demonstration flights.

7.1. *System description*

The overall system setup for the ACTS Aeronautical Terminal Experiment (AEROX) is illustrated in Fig. 22. The system consisted of the ACTS satellite, the Fixed Terminal (FT) located at the NASA LeRC in Cleveland, OH, and the Learjet aeronautical terminal (LJ) visiting several metropolitan areas in the U.S.

The system demonstrated full-duplex voice at 4.8 kbps between the FT and the LJ. Since the FT equipment included a PSTN interface, many attendees at the various demonstration sites were able to experience the quality of seamless voice calls made from the LJ telephone handset.

7.2. *ACTS usage*

The coverage provided by ACTS is illustrated in Fig. 2. As evident in the figure, sixteen isolated metropolitan areas and two contiguous sectors – East and West – are covered in the CONUS. In addition, ACTS provides a mechanically steerable 1.1 meter antenna which produces a relatively larger spot beam covering the hemisphere as seen from 100° W.

The West scan sector was used during the first phase of AEROX when the Learjet flew between Cleveland and Chicago to checkout the system. The West

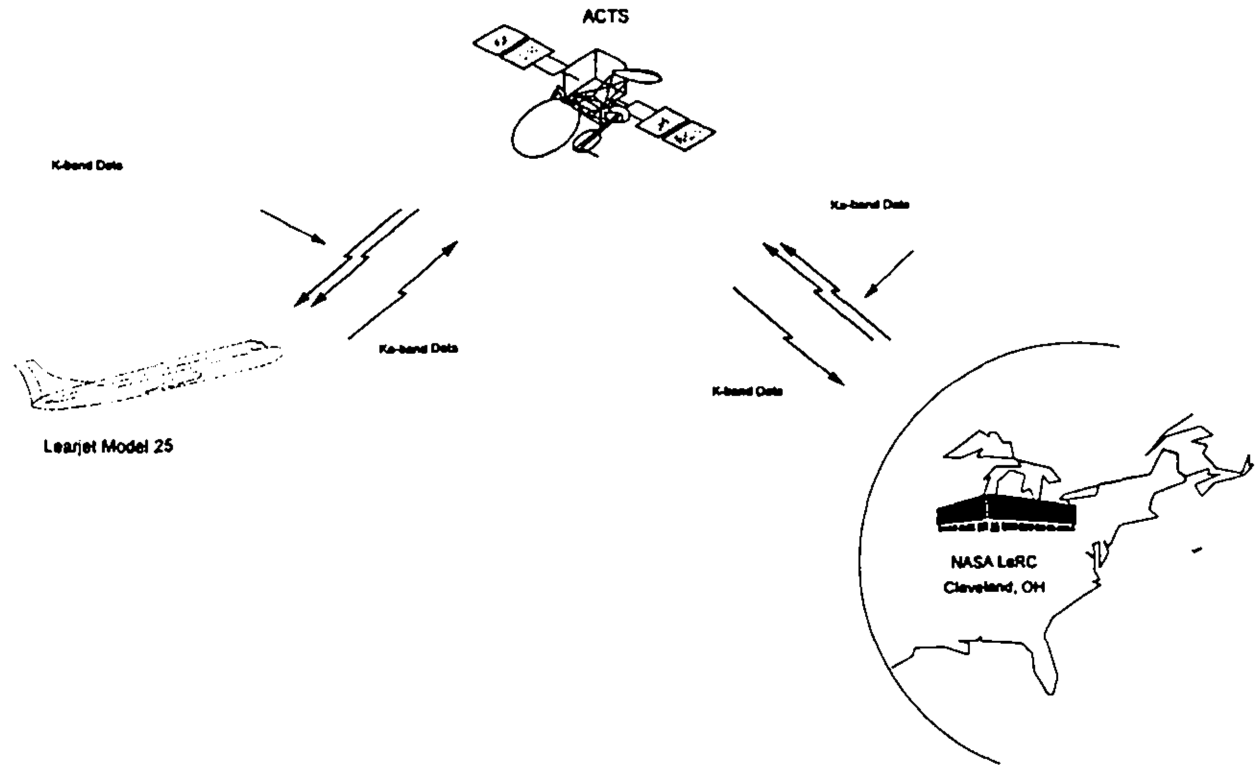

Fig. 22. System setup.

Table 7
ACTS transponder characteristics

	G/T	EIRP
Cleveland	23.10	69.49
Dayton WS19	20.06	65.11
Washington DC	20.40	65.34
Boston, ES4	20.40	65.49
Dallas	22.31	67.77
Los Angeles	21.06	65.34
Seattle	21.16	65.54
Baltimore ES12	20.63	65.34

scan sector is divided into twenty-two spot beam locations, and thus a 'scanning' effect can be achieved by sequentially illuminating the adjacent spots. As the Learjet flew between the two cities, it traversed three spot beam locations and the MBA and MSM configurations had to be controlled in real-time to track the Learjet by using this scanning capability.

Following the first phase of AEROX, the LJ visited eight cities – Cleveland; Dayton; Washington, DC; Boston; Dallas; Los Angeles; Seattle and Baltimore – and gave well-attended demonstrations to audiences consisting of industry and government representatives. The relevant ACTS transponder characteristics for these cities are presented in Table 7.

7.3. *Fixed terminal*

The FT was constructed by interfacing portions of the NASA LeRC LET with portions of the JPL fixed-AMT. A block diagram is presented in Fig. 23.

The LET was developed by NASA LeRC to evaluate the performance of the ACTS satellite in the MSM mode of operation. For this purpose, the LET includes an SMSK modem, a custom bit error rate test unit for data rates ranging from 1.25 to 200 Mbps, an adaptive uplink power control capability to test rain fade compensation algorithms, and an easily accessible IF interface which allows unique IF and baseband equipment to be tested over the ACTS satellite channel. The LET RF components used in the AEROX are a 4.7 meter antenna, a 30 GHz 60 Watt TWTA transmitter, and a 20 GHz low noise receiver. The LET is also responsible for generating the computer commands that control the ACTS satellite configuration in the MSM mode of operation – specifically choosing

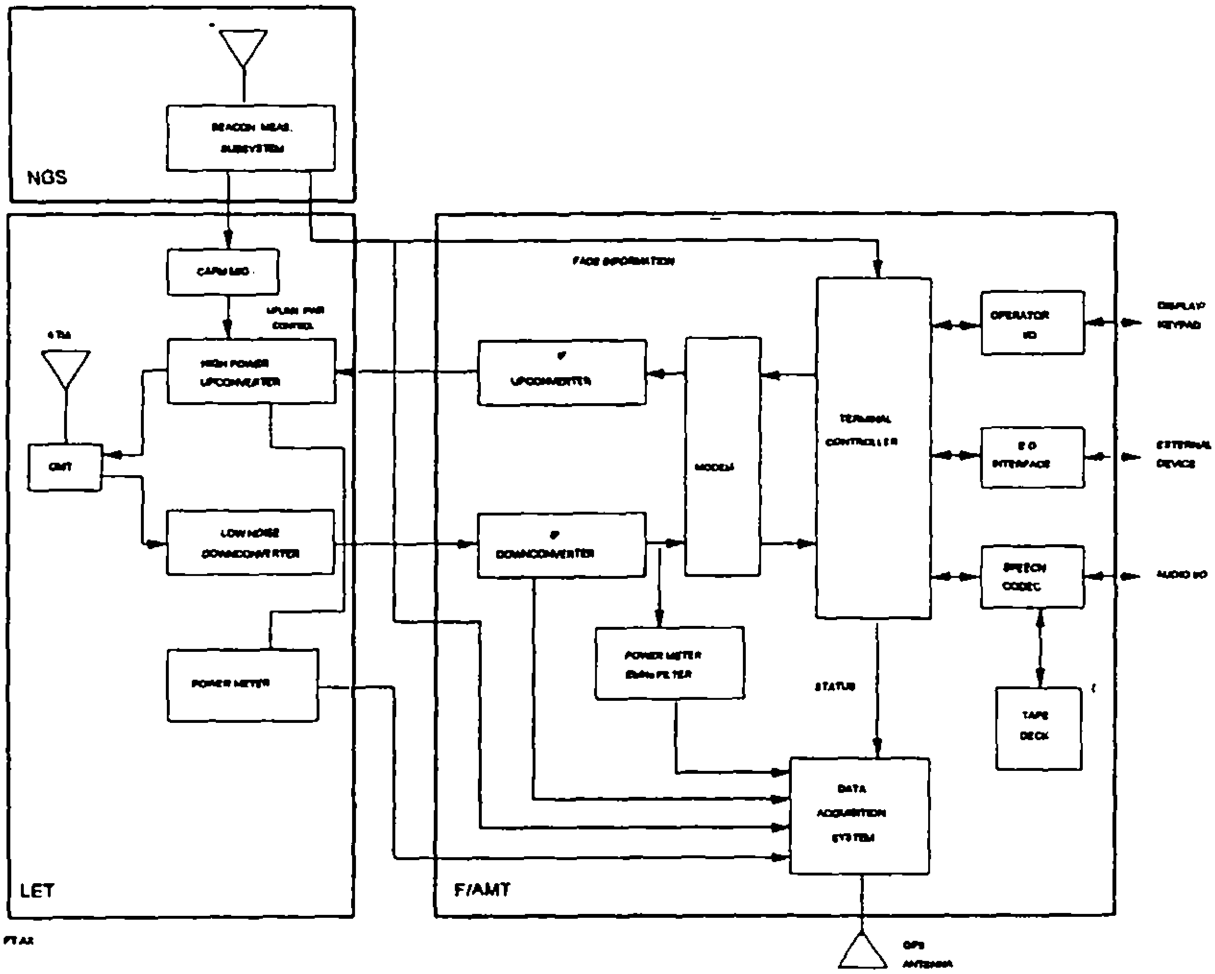

Fig. 23. Fixed terminal.

the spot beams and the connectivity of the MSM.

The AMT was developed for NASA by JPL to demonstrate the viability of speech (at 2.4, 4.8 and 9.6 kbps) and data transmission (at 2.4, 4.8, 9.6 and 64 kbps) in the 30/20 GHz mobile satellite communications environment. The AMT components used at the AEROX FT are the speech CODEC, the modem, the IF Converter (IFC), the TC and the DAS, which have been described previously in this paper.

7.4. *Learjet aeronautical terminal (LJ)*

The Learjet model 25, a NASA LeRC research aircraft, served as the aeronautical mobile platform containing the aeronautical part of the AEROX communications electronics. A block diagram is presented in Fig. 24. The major communications gear consisted of the NASA LeRC 30/20 GHz phased array antenna system and the JPL AMT.

The phased array antenna system consisted of one transmit array antenna and two receive array antennas. The antennas were mounted inside the Learjet looking out the standard Plexiglas windows. Both receive array antennas were mounted, one on each side of the fuselage. The transmit array antenna had to be moved from side to side – depending on the LJ flight profile. These array antennas incorporated individual GaAS MMIC devices for the individual radiating elements for electronic beam steering and distributed power amplification. An open loop antenna controller developed by the NASA Lewis Research Center used information from GPS and aircraft gyroscopes to electronically steer the array beams toward ACTS during flight.

Table 8
Outbound link budget

FT uplink frequency	29.644	GHz
LET EIRP	58.30	dBW
LET pointing	−0.80	dB
LET pol mismatch	−0.13	dB
Path loss	−213.45	dB
Atmosphere loss	−0.364	dB
Rain loss	0.00	dB
ACTS Cleveland G/T	23.10	dB/K
Antenna gain	52.90	dBi
ACTS beam contour	0.00	dB
Uplink C/N_0	90.75	dB-Hz
Uplink CNR	−0.04	dB
Effective BW	1200.0	MHz
Limiter effect	0.00	dB
Eff. uplink CNR	−0.04	dB
Eff. uplink C/N_0	90.75	dB-Hz
Downlink to LJ frequency	19.924	GHz
ACTS Seattle EIRP	65.54	dBW
ACTS S/(S + N)	−3.03	dB
ACTS beam contour	−1.00	dB
Path loss	−210.11	dB
Atmosphere loss	−0.502	dB
Rain loss	0.00	dB
LJ G/T	−17.20	dB/K
LJ pointing error	−0.50	dB
LJ pol. mismatch	−0.85	dB
Downlink C/N_0	60.94	dB-Hz
Outbound link		
Achieved C/N_0	60.94	dB-Hz
Required C/N_0	46.31	dB-Hz
Bit rate	4.80	kbps
AWGN E_b/N_0	6.00	dB
Modem implem.	1.00	dB
Frequency offset phase noise	2.50	dB
Performance margin	14.62	dB

Table 9
Inbound link budget

FT uplink frequency	29.624	GHz
LJ EIRP	23.40	dBW
LJ pointing loss	−0.50	dB
LJ window loss	−2.22	dB
LJ pol. mismatch	−0.85	dB
Path loss	−213.56	dB
Atmosphere loss	−0.364	dB
Rain loss	0.00	dB
ACTS Seattle G/T	21.16	dB/K
Antenna gain	50.80	dBi
ACTS beam contour	−5.00	dB
Uplink C/N_0	50.67	dB-Hz
Uplink CNR	−40.13	dB
Effective BW	1200.0	MHz
Limiter	−1.05	dB
Eff. uplink CNR	−41.18	dB
Eff. uplink C/N_0	49.62	dB-Hz
Downlink to FT frequency	19.904	GHz
ACTS Cleveland EIRP	69.49	dBW
ACTS S/(S + N)	−41.18	dB
ACTS beam contour	0.00	dB
Path loss	209.99	dB
Atmosphere loss	−0.502	dB
Rain loss	0.00	dB
LET G/T	27.48	dB/K
Antenna gain	57.56	dBi
LET pointing loss	−0.50	dB
LET pol. mismatch	−0.13	dB
Downlink C/N_0	73.26	dB-Hz
Inbound link		
Achieved C/N_0	49.60	dB-Hz
Required C/N_0	46.31	dB-Hz
Performance margin	3.28	dB

significant loss through the standard Plexiglas window in the Learjet – measured transmission efficiency of about 60% – and with an estimated combined total of about 1.4 dB for pointing error and polarization mismatch, the calculation shows a margin of about 3.3 dB for the inbound link. Thus the inbound link was completely uplink-limited.

7.6. Link performance data

The inbound carrier and noise in the receiver chain at the FT was measured by an HP power meter via a calibrated 31.8 kHz bandpass filter in the DAS. A personal computer controlled the power meter – and a spectrum analyzer – and recorded power measurements about every 2 seconds. This data was processed to separate the power in the carrier from that in the noise. Since the rotary attenuator in the FT downconverter had to be changed several times during the demonstration, data processing involved subtracting out the effects of the changes made to the downconverter and determining noise interference by using data when the LJ was not transmitting.

The inbound link carrier-to-noise density ratio, C/N_0, recorded during the Seattle demonstration flight on August 4, 1994, is plotted with respect to Greenwich Mean Time (GMT) in Fig. 25. Also plotted in Fig. 25, are the rectangular symbols representing the calculated C/N_0 values.

The Learjet flight path corresponding to this data is plotted in Fig. 26, along with the 10, 5, 3 and 1 dB contours of the ACTS uplink spot beam for Seattle. The Learjet flight path is obtained from a notebook computer which recorded GPS coordinates and time. The ACTS beam contours are predictions based on ground pattern measurements before launch of the ACTS satellite.

To correlate Learjet movement with time, the Learjet latitude coordinates are plotted with respect to neg-

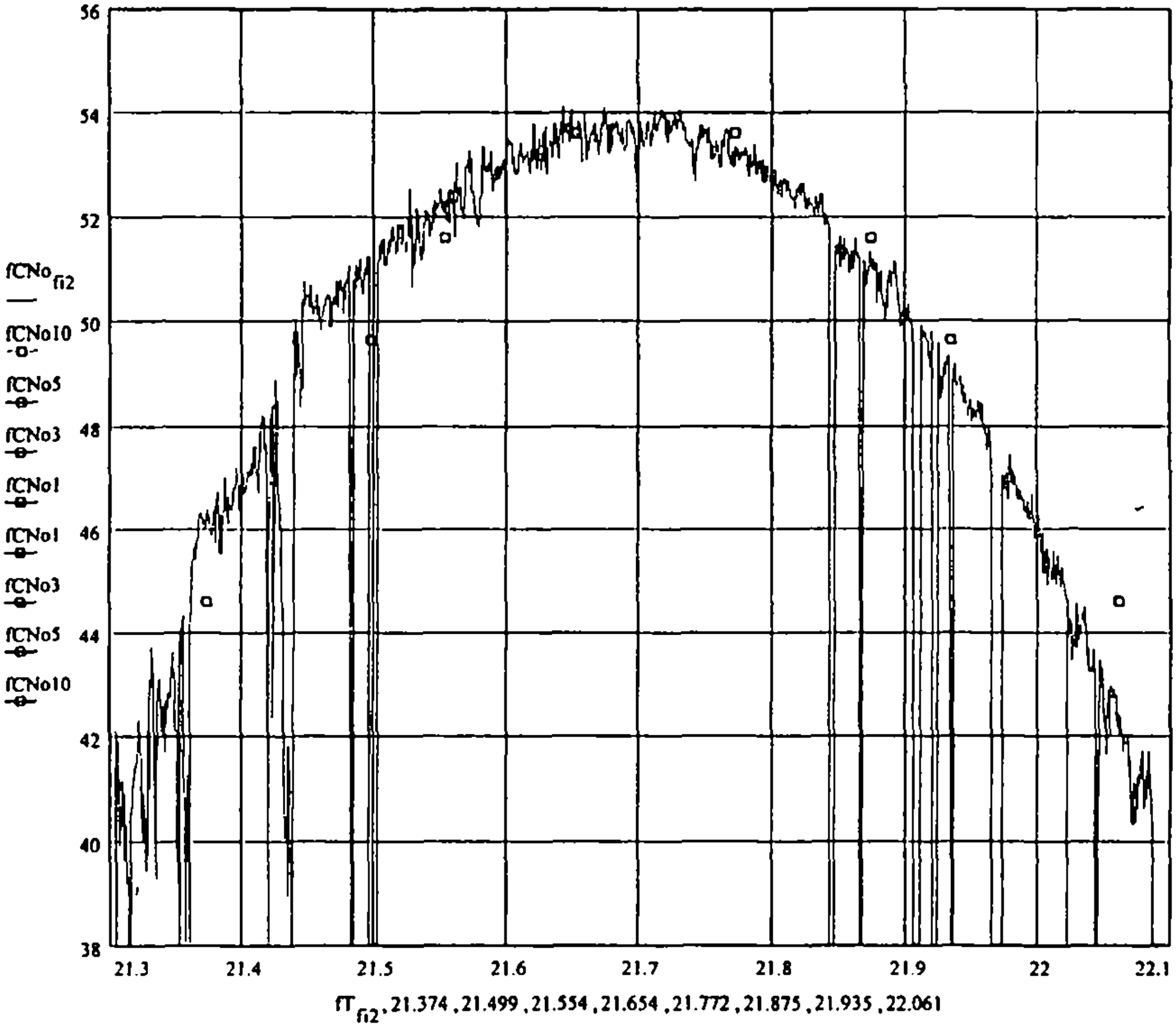

Fig. 25. Inbound link C/N_0 vs. GMT.

ative values of GMT in Fig. 27. The Learjet flew South-West at an altitude of about 43,000 ft. and crossed 48.15N, 47.87N, 47.66N, 47.26N, 46.78N, 46.36N, 46.12N and 45.62N latitude lines at about 21.37, 21.50, 21.55, 21.65, 21.77, 21.87, 21.93 and 22.06 GMT, respectively. According to the data, these coordinates and times correspond to Learjet entering (and subsequently exiting – in reverse order) 10, 5, 3 and 1 dB contours. The inbound link budget calculation predicts C/N_0 to be 44.6, 49.6, 51.6 and 53.6 dB-Hz for LJ at 10, 5, 3 and 1 dB contours, respectively. As shown in Fig. 27, measured performance supports these predictions very closely. The data does suggest that the spot beam position is shifted – relative to the prediction – toward East by a small amount. Good quality full duplex voice communication with LJ and FT/PSTN continued until about 22.0 GMT. Afterwards, the voice quality degraded rapidly and the flight was aborted at about 22.1 GMT with the LJ well outside the 10 dB contour.

Outbound link parameters were recorded at the LJ, but could not be processed due to a number of complications. For example, an accurate assessment of the FT EIRP could not be made – the rotary attenuator in the FT transmit chain was found to be faulty and the transmit power was not recorded in real-time.

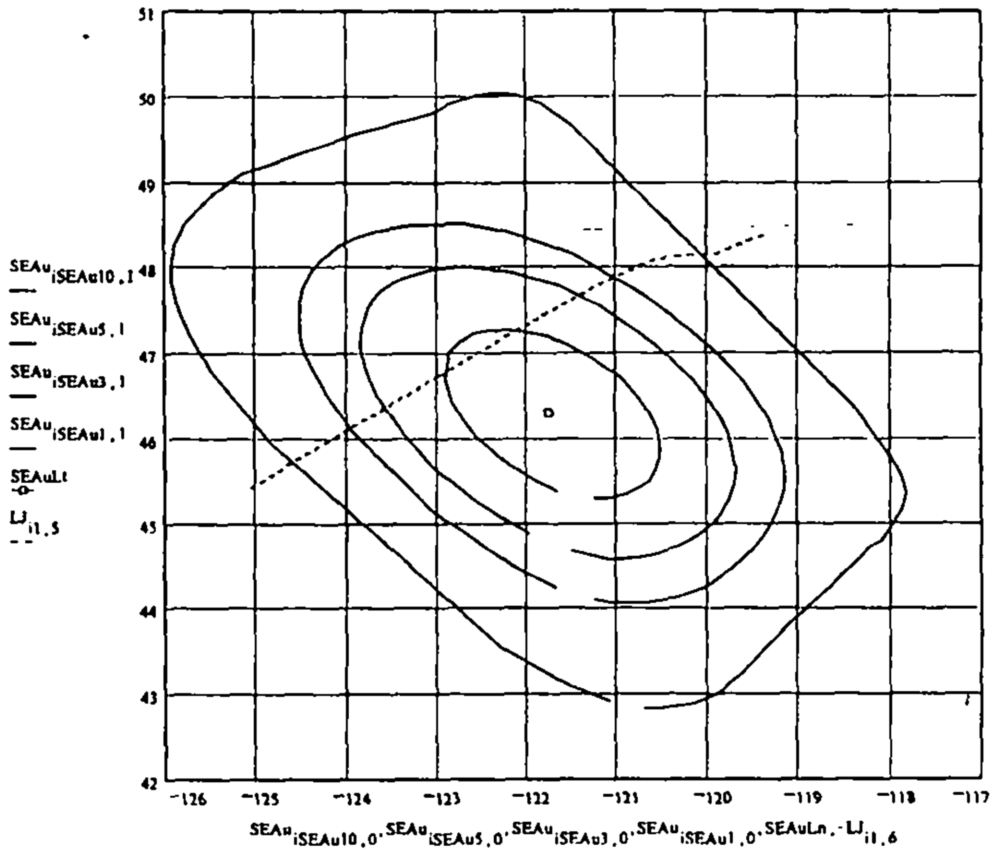

Fig. 26. Seattle beam contours and learjet trajectory.

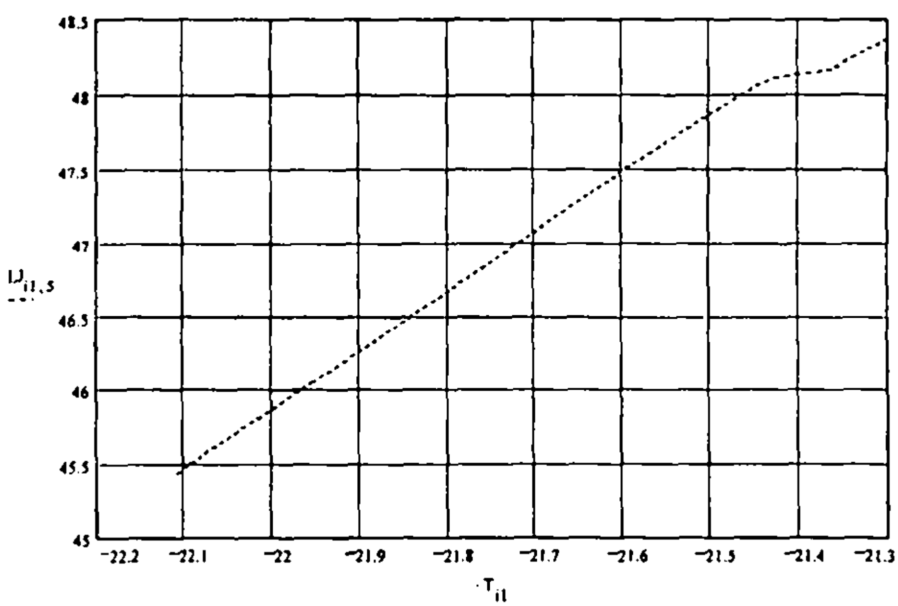

Fig. 27. Learjet latitude vs. GMT.

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7.7. Summary of results

The AEROX Program provided an opportunity to showcase many proof-of-concept technologies in the ACTS satellite, the active phased array antennas and the AMT. Also, good correlation has been found between predicted and measured performance during the demonstration flight over Seattle.

8. Conclusion

The ACTS mobile experiments that have been completed, have demonstrated the use of Ka band to provide voice and data communications to mobile terrestrial and aeronautical users. Both reflector and phased array antennas have been employed and techniques have been developed to maintain contact with the spacecraft as the mobile vehicle changes orientation and position along its travel. Data has also been collected to show the effect of obstacles along the path of travel for terrestrial vehicles.

In the case of the aeronautical experiments, high data rates to support real-time video to/from aircraft have been demonstrated, and additional experiments to be performed in 1996 will provide data to evaluate the commercial potential of this type of service.